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Mixed basalt-rhyolite assemblages in Yellowstone National Park: The petro-genetic significance of magma mixing

Debra Winter Struhsacker
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MIXED BASALT-RHYOLITE ASSEMBLAGES IN YELLOWSTONE NATIONAL PARK

THE PETROGENETIC SIGNIFICANCE OF MAGMA MIXING

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B.A., Wellesley College, 1974

Presented in partial fulfillment of the
requirements for the degree of

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ABSTRACT

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Mixed Basalt-Rhyolite Assemblages in Yellowstone National Park: The Petrogenetic Significance of Magma Mixing

Director: David Alt

The Gardiner River and Geode Creek mixed basalt-rhyolite assemblages outcrop in the north-central portion of the Quaternary bimodal volcanics in Yellowstone National Park. The Gardiner River lavas include striking "marble-cake" rocks evidently produced as a basaltic magma contaminated a rhyolitic magma, hybridizing both components. The Geode Creek lavas are a homogeneous, basaltic-looking rock, containing quartz and alkali feldspar grains rimmed by augite, and resorbed inclusion-laden crystals of plagioclase with sodic cores and calcic rims. These features imply contamination of a basaltic magma by a rhyolitic magma. A survey of these Yellowstone mixed lavas and similar mixed assemblages in the Cascades, the San Juan Mountains, Iceland, Scotland, and Ireland suggests that mixing occurs at shallow crustal levels, most commonly in an extensional tectonic setting. The Cascade examples, although spatially related to a subduction zone, appear to be shallow magmatic features. Mixing evidently occurs as primary basalt and rhyolite meet. Shallow, extensional environments inhibit mixing because lack of water limits diffusion and the short distance between the site of mixing and eruption limits opportunity for mechanical stirring. Deeper magma chambers, such as those in subduction zones, with higher water content and greater opportunity for stirring, produce well-mixed, nearly homogeneous lavas. Thus, in light of this proposed model, magma mixing may play a significant role in the generation of arc andesites which commonly exhibit many disequilibrium features similar to those observed in the Yellowstone mixed lavas.

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CHAPTER I

INTRODUCTION

The purpose of this investigation is to study the petrologic and tectonic parameters of magma mixing. This work examines in detail two mixed basalt-rhyolite assemblages from Yellowstone National Park, and compares and contrasts these lavas with other mixed basalt-rhyolite lavas throughout the world. An attempt is made to establish some criteria for recognizing mixed lavas, discuss the physical processes involved when two contrasting magmas mix, outline the tectonic setting or settings of magma mixing, and suggest the petrogenetic significance of magma mixing.

Although mixed basalt-rhyolite lavas outcrop throughout the world, volumetrically they comprise a very small portion of most volcanic piles. Thus, it appears that mixed assemblages, such as those found in Yellowstone Park, are a rarity. However, considering the vast quantities of basalt and rhyolite erupted in a bimodal volcanic field such as the Yellowstone region, there is a high probability of occasional, if not routine, contact of rhyolitic and basaltic melts, with the attendant opportunity for these two magmas to interact. The paucity of mixed lavas thus seems strange. This scarcity may actually reflect the difficulties and subtleties involved in identifying a hybrid lava produced by magma mixing. Although some mixed assemblages, such as the Gardiner River complex in Yellowstone National Park, are easily recognized, the evidence of magma mixing is much more subtle in other examples, like the Geode Creek lavas of Yellowstone Park. Perhaps the frequency and importance of magma mixing has been largely overlooked because mixed assemblages are often difficult to identify. A review of the characteristics of mixed magmas and of the petrogenetic significance of mixing is thus appropriate.

The first portion of this study is a brief discussion of the geology and tectonic setting of Yellowstone National Park, and a detailed description of mixed magmas within the Park. The Yellowstone mixed magmas are then compared to other mixed basalt-rhyolite complexes in the United States, Iceland, and Great Britain. In conclusion, a magma mixing model is proposed to explain the physicochemical and tectonic parameters controlling magma mixing.

CHAPTER II

GEOLOGIC SETTING OF THE YELLOWSTONE REGION

The Yellowstone area has a fascinating and varied geologic history. A complete treatment of this history is beyond the scope of this paper, which is mainly concerned with Quarternary events. However, a brief consideration of the pre-Quaternary history is necessary in order to place the Quaternary geology into the proper framework. Keefer (1972) offers an excellent review of the geologic history of Yellowstone National Park.

Pre-Tertiary Lithologies

Outcrops of pre-Tertiary rocks are limited to northern, northwestern, and southern Yellowstone Park. Precambrian lithologies in the area form a high-grade regional metamorphic terrane consisting primarily of 2.6 and 1.6 billion year old granitic biotite orthogneiss and quartz-biotite paraschist (Ruppel, 1972). Dominant orientations in this Precambrian basement include N 20 E and N 50 E foliation trends and N 80 W, N 60 W, and N 20 E joint trends (Ruppel, 1972). These directions may have influenced later tectonic and volcanic developments (Eaton and others, 1975). Paleozoic and Mesozoic sedimentary rocks form a section approximately 2.2 km thick consisting dominantly of Paleozoic platform-type carbonates and Mesozoic clastics (Ruppel, 1972).

Volcanic History of Yellowstone National Park

Since the early Tertiary, volcanism has characterized the geologic history of the Yellowstone region. However, the nature of this volcanism has changed through time from early calc-alkaline lavas to later bimodal volcanics. The first volcanic rocks in the area, the Eocene Absaroka volcanics are a thick pile of andesitic rocks. These were eventually followed by a Quaternary, bimodal basalt-rhyolite volcanic episode with which this paper is primarily concerned.

The Absaroka volcanics of early to Late Eocene age blanket a broad area in southwestern Montana and northwestern Wyoming; they are the largest of the many Eocene volcanic fields scattered throughout the western United States. The Absaroka volcanic pile is largely calc-alkaline andesitic and dacitic extrusives with lesser potassic, alkaline mafic lavas, minor rhyodacite ash flow tuffs and numerous small intrusives. The volcanics rest unconformably upon deformed Precambrian to Paleocene rocks (Smedes and Prostka, 1972).

Quaternary Volcanism in Yellowstone National Park

The Quaternary volcanics of Yellowstone National Park are a strictly bimodal assemblage of rhyolite and basalt, with rhyolite greatly predominant. Volcanics of intermediate composition are absent except for the mixed basalt-rhyolite complexes discussed in this paper.

The Yellowstone volcanic terrane consists of two parts: an outer ring of rhyolitic welded tuffs with subordinate rhyolite and basalt marginal lava flows, and an inner zone covered mainly by rhyolite flows (Boyd, 1961). The volcanics cover Precambrian to early Quaternary rocks. In many areas, especially in eastern Yellowstone National Park, they overlie Eocene Absaroka volcanics (Christiansen and Blank, 1972).

Three catastrophic episodes of bimodal volcanism and caldera collapse punctuate the Quaternary history of Yellowstone Park. Collectively, the volcanics erupted during these three events comprise the Yellowstone Group as named by Christiansen and Blank (1972). All stratigraphic nomenclature used in this paper follows their scheme.

Each caldera collapse produced extensive rhyolitic welded ash flow sheets and lesser marginal pre- and post-caldera rhyolite and basalt flows. These welded tuffs are commonly devitrified and contain phenocrysts of quartz, sanidine, and sodic plagioclase with minor iron oxide, clinopyroxene, fayalite, and hornblende phenocrysts. The 2.0 million year old Huckleberry Ridge Tuff is the oldest formation within the Yellowstone Group. The 1.2 million year old Mesa Falls Tuff Formation, produced by the eruption of the Island Park caldera west of the Park boundary, does not outcrop in Yellowstone Park. The latest caldera event, 0.6 million years ago, produced the Lava Creek Tuff Formation which blankets a large area of the Park (Christiansen and Blank, 1972). The mixed basalt-rhyolite lavas of Geode Creek and along the Gardiner River (Fig. 1) formed during this latest volcanic cycle.

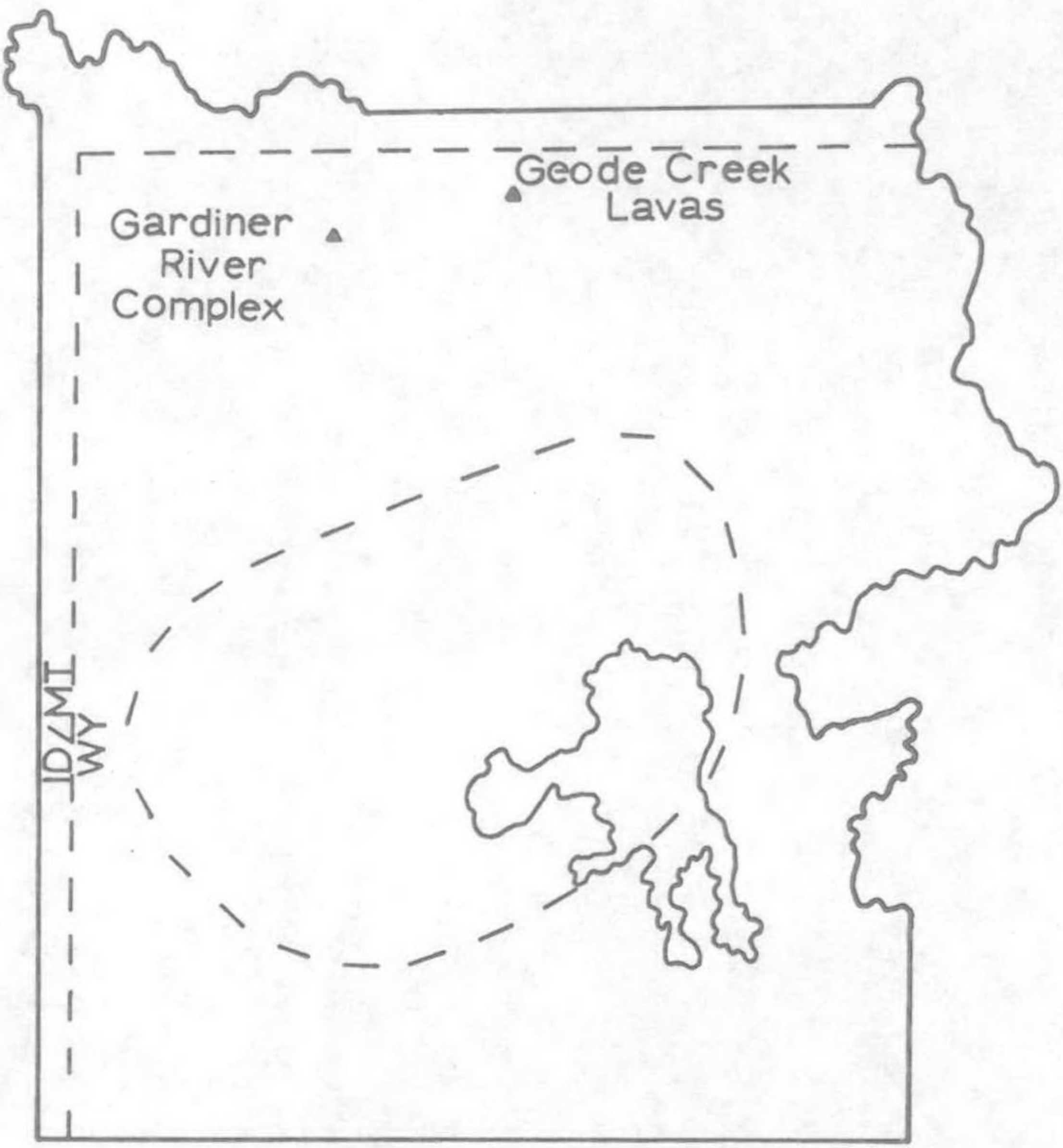

Figure 1. Map of Yellowstone National Park showing the position of the Gardiner River and Geode Creek mixed basalt-rhyolite assemblages. The dashed, circular line is the outline of the Yellowstone caldera.

The 0.6 million year old caldera (Fig. 1) dominates the Yellowstone landscape. It is a chasm 45 km wide and 70 km long (Eaton and others, 1975). This caldera formed as doming above twin shallow magma chambers gradually produced a system of ring fractures from which lava issued. Finally, in a catastrophic explosion of glowing ash, these magma chambers rapidly emptied. This sudden removal of vast volumes of magma triggered caldera collapse as the magma chamber roofs subsided along large, vertical normal faults. The amount of subsidence must have amounted to as much as a kilometer (Keefer, 1972). Immediately following this subsidence, two resurgent domes began forming above the two magma chambers as rhyolite magma again ascended. As magma reached the surface, vast quantities of rhyolite, with lesser obsidian and basalt lava, flowed from the ring fracture system overlying the twin magma chambers and partially filled the caldera. Some of these caldera lavas erupted as recently as 60,000 years ago (Keefer, 1972).

Magma Beneath Yellowstone National Park

Geophysical data compiled by Eaton and others (1975) suggests the presence of a large, shallow (less than 5 km) partially molten rhyolitic magma body beneath Yellowstone Park. This body marks a zone of low gravity and magnetic anomalies, and of high seismic attentuation. Eaton and others (1975) envision this silicic magma body as lying atop an even greater volume of mechanically and thermally disturbed crustal and mantle rocks containing pods of basaltic and silicic magma that extend some 50 km into the mantle. Crystallization of the upper, silicic portion will eventually form a granitic batholith.

Expanding upon this idea, Christiansen and Blank (in press) suggest that all caldera-dominated rhyolitic volcanic fields are underlain by crystalline or partially molten shallow level granitic batholiths. In this manner, these silicic volcanics are but a fraction of the total volume of magma emplaced within the upper crust. In support of this theory, Christiansen and Blank (in press) cite the location of the caldera-marginal Yellowstone basalt flows. Dense basaltic magma cannot rise through partially molten rhyolite. Basalts generated in the mantle beneath the proposed Yellowstone batholith can only rise along the margins of this rhyolitic body, thus explaining their restruction to sites outside the caldera margin. During their ascent, these caldera-marginal basalts locally encounter rhyolite with which they may mix, thereby producing the mixed basalt-rhyolite complexes observed in Yellowstone Park. These mixed assemblages like the basalt flows, are restricted to the caldera periphery (see Fig. 1).

It should be noted, however, that in contrast to the 0.6 m.y. old, rhyolite-dominated Yellowstone caldera, the 1.2 m.y. old Island Park caldera is covered with basalts rather than rhyolites. Christiansen and Blank (in press) suggest that voluminous basaltic volcanism commenced in the Island Park area as soon as the granitic batholith underlying the Island Park caldera crystallized sufficiently to allow fracturing and vertical transmission of basaltic magmas. Likewise, basalt flows should bury the Yellowstone area as soon as the batholith beneath Yellowstone solidifies.

CHAPTER III

REGIONAL TECTONIC SETTING OF THE YELLOWSTONE REGION

Since one of the goals of this paper is to determine the tectonic environment or environments of magma mixing, it is appropriate to consider the tectonic setting of Yellowstone Park. Unfortunately, the tectonic framework of this area is poorly understood. Many workers attempt to explain Yellowstone tectonics in terms of continental margin, subduction-style tectonics. For example, Lipman and others (1972) and Christiansen and Lipman (1972) correlate the stepwise subduction of the East Pacific Rise with the progressive initiation of bimodal volcanism throughout the west. Hyndman (1972) on the other hand, considers the Yellowstone bimodal province as the miogeoclinal equivalent of the basalt-andesite-rhyolite suite characteristic of subduction zones. However, marginal tectonics may not be effective as far inland as the Yellowstone region.

An alternative approach to Yellowstone tectonics is the mantle plume model embraced by Morgan (1972a, 1972b), Eaton and others (1975), Smith and Sbar (1975), and Suppe and others (1975). According to this model, the Yellowstone and adjacent Snake River Plain bimodal volcanic provinces mark the trace of a mantle plume moving northeastward relative to the North American plate. Eaton and others (1975) suggest that this plume may be "navigating" along northeast-trending zones of weakness in the Precambrian basement. The plume idea has attracted many supporters largely because it provides a reasonable explanation for the northeastward transgressive volcanism observed along the Snake River Plain-Yellowstone trend. The very recent volcanic activity in Yellowstone Park reflects the current position of this proposed mantle plume.

An understanding of the tectonic setting of Yellowstone Park cannot be gained without also considering the closely-related Snake River Plain volcanic province. Like the Yellowstone area, the Snake River Plain is dominated by bimodal volcanism and extensional tectonics (Christiansen and Lipman, 1972; Suppe and others, 1975, and Prostka, 1975). Bimodal volcanism in the Yellowstone-Snake River Plain region is time transgressive, starting in the southwestern Snake River Plain near Boise in the lower Pliocene and migrating northeastward to its present position in Yellowstone Park (Armstrong and others, 1975, and Eaton and others, 1975). Everywhere in the region, rhyolitic caldera-forming pyroclastics precede quiet basaltic lava flows. According to Christiansen and Blank (in press) this specific volcanic sequence of rhyolite followed by basalt is dictated by the inability of basalt to rise through partially molten silicic material.

In this manner, silicic volcanism began 15 million years ago in the western Snake River Plain and 5 million years ago in the eastern Snake River Plain. This silicic phase reached the Yellowstone Park area two million years ago. Basaltic volcanism in the Plain began about 10 million years ago and has not yet moved east of the Island Park area (Armstrong and others, 1975). According to this transgression model, the Yellowstone Park area remains in an early stage of development, namely the primary silicic stage. If the Yellowstone region is indeed part of the Snake River Plain trend, basalt flows will eventually cover it (Christiansen and Lipman, 1972). It is interesting that this same sequence of early siliceous volcanics followed by basalts is reported by Armstrong and others (1969) for the Basin and Range Province.

Other parallels relate the Basin and Range Province to the Yellowstone-Snake River Plain area. Most notably, the Cenozoic volcanic histories of these areas are quite similar. Both regions experienced widespread early Tertiary intermediate volcanism, followed by late Cenozoic bimodal volcanism and associated regional extension (Lipman and others, 1972; Christiansen and Lipman, 1972). Although the significance of this pattern is not fully understood, its widespread distribution suggests that any tectonic model for the western United States must consider this volcanic sequence.

Establishing a unified Cenozoic tectonic picture for the Yellowstone-Snake River Plain area poses a very difficult problem. Any model must consider both the intermediate and bimodal volcanics so well developed in this region, as well as their relationship, if any, to marginal tectonics. It seems likely that more knowledge of the Yellowstone-Snake River Plain province will certainly improve our understanding of the Cenozoic tectonic history of the entire western United States.

CHAPTER IV

CHEMISTRY AND TECTONICS OF BIMODAL VOLCANISM IN THE NORTHWEST

Bimodal volcanic provinces occur world wide. The formation of this basalt-rhyolite association is apparently restricted to regions of continental extension (Hyndman, 1972, p. 120). In addition, the composition of basalts and rhyolites formed in bimodal volcanic fields is fairly consistent everywhere. In a comparison of Yellowstone basalts and rhyolites with other bimodal lavas throughout the world, Christiansen and Blank (in press) show that bimodal rhyolites are low in Al and Ca, are relatively high in Si, and have a high total Fe to Mg ratio when compared to rhyolites associated with calc-alkaline, andesitic suites. Bimodal basalts on the other hand, as typified by the Yellowstone-Snake River Plain basalts form two chemically distinct suites. One suite, the basalts marginal to the Yellowstone Plateau and to the Snake River Plain are relatively low in K, Ti, P, F, have a low Fe/Mg ratio and are high in Ca. This chemistry resembles that observed in tholeiites formed at mid-oceanic ridges. In comparison, the second suite has high K, Ti, P and F. The Yellowstone Plateau basalts and Snake River Plain basalts belong to this second group. This basalt composition has both tholeiitic and alkaline affinities. The high K content of this suite resembles that observed in ocean island and continental tholeiites. However, the high Ti, P and F content of these basalts resembles that of alkaline basalts in oceanic and continental regions.

These chemical similarities between bimodal basalts and oceanic basalts, as well as their shared extensional tectonic environment leads Christiansen and Blank (in press) to suggest that bimodal basalt-rhyolite volcanism is the continental equivalent of oceanic basaltic volcanism. Despite the many similarities between these two suites, perhaps grouping bimodal volcanics and continental flood basalts forms a more useful and closely related petrotectonic association. Both bimodal basalts and continental flood basalts range from tholeiitic to alkaline in composition. Moreover, the Yellowstone-Snake River Plain bimodal province is closely related in time and space to the Columbia River Plateau flood basalts. Seen on a regional scale, extensional tectonics and basaltic volcanism in the northwestern United States began in the mid-Miocene with eruption of the Columbia River Plateau basalts. Some of these basalts are contemporaneous with the earliest rhyolitic volcanism in the Snake River Plain about 15 m.y. ago (Armstrong and others, 1975).

This spatial and temporal juxtaposition of the Columbia River flood basalts and the Snake River Plain-Yellowstone bimodal trend suggests a genetic relationship. In fact, these two volcanic provinces may have formed in response to the same plate tectonic conditions. The only obvious difference between the two areas is the presence of rhyolite in the Snake River Plain-Yellowstone province, and its absence in the Columbia River Plateau basalts. This distribution of rhyolite can be readily explained by considering the position of continental basement rocks in the Northwest. As shown in Figure 2, the Columbia basalts formed in areas underlain by oceanic crust, whereas the bimodal Snake River-Yellowstone rhyolites and basalts developed in areas obviously underlain by continental basement. In this manner continental flood basalts and bimodal volcanics form a coherent petrotectonic association. Flood basalts form in extensional terranes underlain by oceanic crust, whereas bimodal volcanics develop in extensional terranes underlain by continental crust.

As suggested by Christiansen and Blank (in press), basaltic volcanism in extensional terranes is caused by partial melting of mantle peridotites, presumably due to stress release during regional extension. If these basalts form beneath continental crust, heat from the rising basalt may cause partial melting of the lower portions of this continental basement. Thus rhyolitic melts are generated in areas of continental crust due to the ascent of mantle-derived basalt. Moreover, rhyolites generated in this manner will erupt prior to the basalts, accounting for the observed rhyolite to basalt sequence observed in the Snake River Plain-Yellowstone area.

Unfortunately, the ultimate tectonic cause of late Cenozoic to Recent extension in the Northwest remains a mystery. However, the identical tectonic style and overlapping chronology of volcanism in the Columbia River Plateau and the Snake River Plain-Yellowstone area indicates a strong genetic affinity between these two regions. Quite

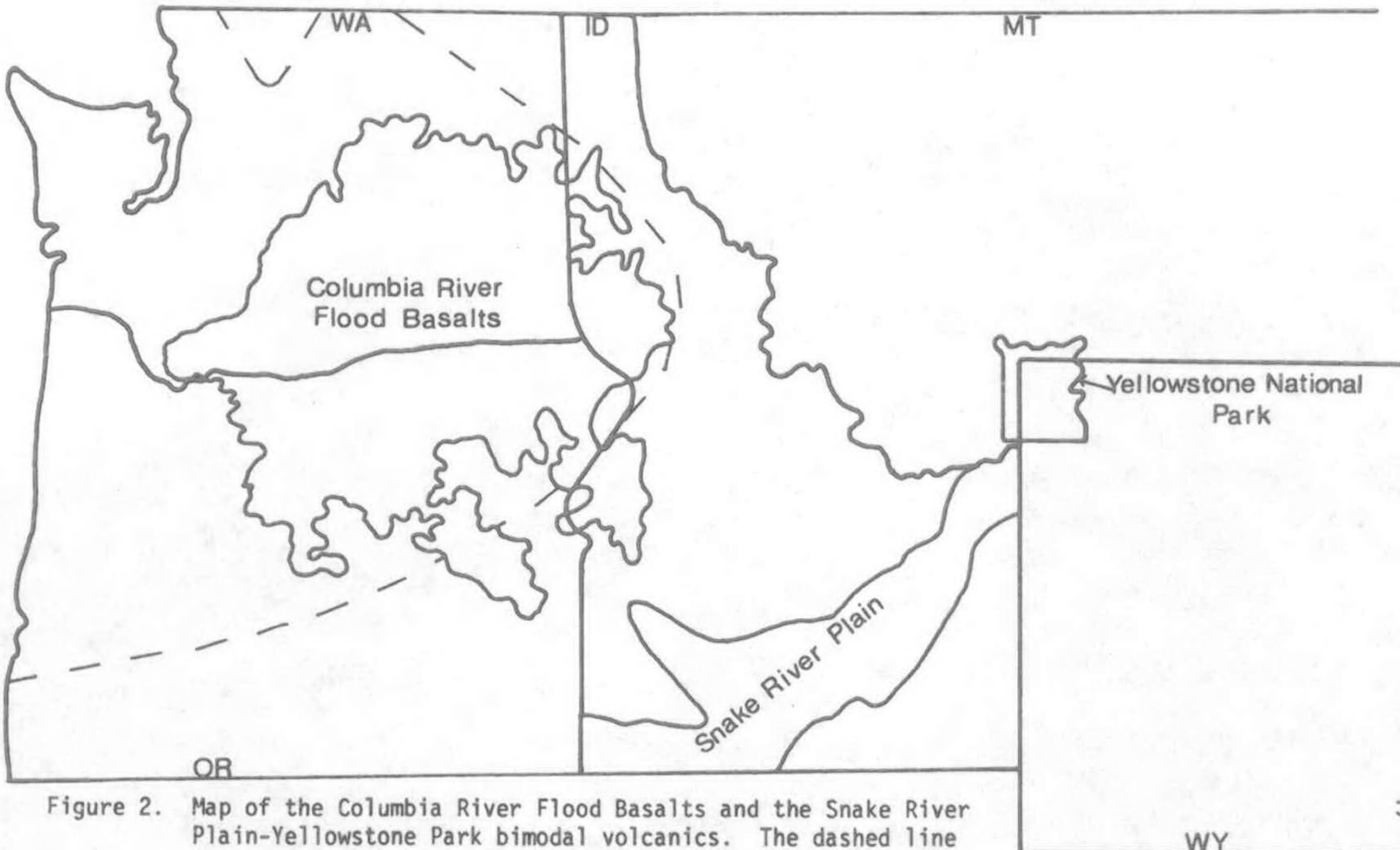

Figure 2. Map of the Columbia River Flood Basalts and the Snake River Plain-Yellowstone Park bimodal volcanics. The dashed line is the inferred western margin of continental crustal rocks. Modified after Alt and Hyndman (1978).

possibly this regional extension is related to the progressive subduction of segments of the East Pacific Rise (Atwater, 1970). The correlation between this change in tectonic configuration and the progressive shift from a compressional environment dominated by calc-alkaline volcanism, to an extensional regime characterized by basaltic and bimodal basaltic-rhyolitic volcanism is well documented (Christiansen and Lipman, 1972; Lipman and others, 1972).

CHAPTER V

MIXED BASALT-RHYOLITE COMPLEXES IN YELLOWSTONE NATIONAL PARK

The Geode Creek Complex

The Geode Creek complex (Fig. 1, p.6), outcrops both north and south of the Grand Loop Road between Mammoth Hot Springs and Tower Junction. Both outcrops are within one half a mile from the road. This complex consists of massive, steeply-dipping aphanitic grey basalt, overlain by a brick red, locally brecciated, scoriaceous basalt. The massive texture and steep dips of the grey basalt suggest that this is a dike rock. The brick red scoria is interpreted as the rubbly, basal portion of a lava flow. Most of the breccia fragments in the scoria resemble Tertiary volcanic rocks in the area.

The southern outcrop is dumbell-shaped with a general north-northwest trend. The basalt-scoria contact, where exposed, is very clean and sharp with no evidence of baking. Locally fragments of the aphanitic basalt occur in the scoria adjacent to the scoria-basalt contact. It appears that the dike rock is older than the lava flow. Prostka and others (1975) map the aphanitic basalt as a dike, an interpretation consistent with the steep dips of the basalt.

The outcrop north of the road shows essentially the same relationships, although a large pile of talus obscures some of the contacts. The lithologies north of the road resemble those previously described except that the northern scoria is more vesicular than that south of the road. Prostka and others (1975) have not mapped the dike north of the road. They describe this outcrop as a lava flow similar to the southern flow.

In hand sample, both the dike rock and the scoria appear to be normal, basaltic-looking rocks. However, closer examination reveals unusual-looking, glassy lath-shaped crystals and sparse, glassy round crystals. In thin section, these are identified as plagioclase and quartz xenocrysts respectively. A more detailed discussion of these xenocrysts follows in the petrography section. In addition to these unusual xenocrysts, several of the Geode Creek specimens also contain coarse-grained inclusions.

The Gardiner River Complex

Mixed basalt-rhyolite lavas extend for 300 meters along the Gardiner River as it flows northeastward from the Sheepeaters Cliff area, 8 km south of Mammoth Hot Springs (Fig. 1, p. 6). These outcrops are easily reached by a trail that begins at the Sheepeaters Cliff Amphitheatre parking lot and parallels the Gardiner River for about 250 meters.

The complex is best exposed along the northern bank of the river above the first cataract. The lavas form a nearly endless variety of mixed basalt-rhyolite textures and structures including angular, round, or crenulated inclusions of basalt in rhyolite, irregular stringers and dikelets of rhyolite intrusive into basalt and "marble-cake" swirls of basalt and rhyolite. Changes in texture and rock type are abrupt rather than gradational; a dominantly basaltic-looking rock may lie immediately adjacent to a rhyolitic-looking rock. In hand sample, both the basaltic and rhyolitic portions are noticeably contaminated. The basaltic-looking lithologies contain numerous xenocrysts of quartz and alkali feldspar visible in hand sample, whereas the rhyolite contains many basaltic inclusions. A more detailed discussion of these features follows in the petrography section.

The Gardiner River complex has received much attention since its discovery in 1899 by Iddings. Later, a great controversy raged between Fenner (1938, 1944) and Wilcox (1944) concerning the origin of this unusual assemblage. Fenner proposed that rhyolite flowed down a preexisting valley of basalt, causing pneumatolytic alteration of the basalt by rhyolite vapors and simultaneous alteration of the rhyolite by basalt. Alternatively, Wilcox (1944) originally contended that two contemporaneous but initially unrelated basalt and rhyolite flows comingled on the surface, forming the present complex. In a recent modification of this theory, Wilcox proposes subsurface mixing of basaltic and rhyolitic magmas (Christiansen, 1977, written communication). Studies by Blake and others (1965) and Walker and Skelhorn (1966) of similar basalt-rhyolite mixed lavas in Great Britain and Iceland support the theory of subsurface mixing prior to extrusion.

CHAPTER VI

PETROGRAPHY OF THE GEODE CREEK LAVAS

In thin section, and in hand sample, the Geode Creek lavas consist of three textural varieties: a fine-grained, porphyritic rock, a moderately scoriaceous lava, and a locally brecciated, porphyritic type. Within each textural subgroup, and throughout the entire complex as well, these lavas are homogeneous, displaying only minor variations in mineralogy. Table 1 presents a summary of the detailed mineralogy of each sample examined.

In general, the lavas of the Geode Creek suite consist of forty to seventy percent dark, commonly glassy groundmass, and sixty to thirty percent phenocryst phases. The phenocryst assemblage includes two different habits of plagioclase, olivine, augite, pigeonite, orthopyroxene, and magnetite. As indicated on Table 1, not all of these phases are present in each sample. In addition, many of these samples contain a small proportion of quartz and alkali feldspar grains. Plutonic inclusions are present in a few samples.

Phenocryst Mineralogy

The following is a description of the phenocryst constituents. The mafic phenocrysts in the Geode Creek suite comprise five to fifteen percent of the rock. As shown in Table 1, olivine is the dominant mafic,

Table 1. Summary of the Mineralogic Variation of the Geode Creek Lavas

Sample #	Groundmass (%)	Small Plag Laths (%)	Large Plag Phenos (%)	Olivine (%)	Augite (%)	Pigeonite (%)	Ortho-pyoxene (%)	Mag-netite (%)	Quartz	K-Felds-par (%)	Presence of Pyro-xene Clots
622-2a	50-60	25	10-15	5-10				1-2		trace	
622-2b	50-60	30-35	10-15	5-8			1	2-3			
622-2c	60	25-30	10	5-7				1-2	trace	trace	yes
622-2d	50	25	10-15	5-7	3		2	1			yes
622-3a	40	15-20	15-20	5-10	2-3			1/2	trace		yes
622-3b	50-60	10-15	10-15	5		3		1-2	1-2		yes
622-6a	60-70	10	10-15	3-5	5		2	1	2	1	
622-6b	40-50	30	10	10	2			2			
623-1a	70-75	10	10	3-5	3-5			1-2	trace		yes
623-2a	60-70	10-15	10	8	5			1	1-2		yes
623-3a	45-40	40	5		3	3	4	2	1-2		
623-3b	50	25-30	10	5	5			1-2			
624-1a	65-70	20	10	5	4		1	1			yes
624-3a	40	35	10	10	3		2	1			yes
GC-1	70	10-15	10	5		3	3	1-2	trace		yes
GC-3	65	15-20	10	3		2	5		1-2		yes

and is present in nearly every sample. Olivine occurs as fine-grained, 0.125 to 0.25 mm subhedral to euhedral grains which are commonly rimmed by iddingsite. The Geode Creek olivine is biaxial positive with a 2V near 90°, indicating a forsteritic composition (Deer and others, 1966, pg. 6). Augite is the second most common mafic phenocryst, forming up to five percent of the phenocryst assemblage. Augite phenocrysts range from 0.125 mm to 0.25 mm, are biaxial positive with a 2V of approximately 60° and are commonly subhedral. Augite is readily distinguished from olivine in these lavas by its lower birefringence and the absence of iddingsite. Variable amounts of pigeonite and orthopyroxene also occur as phenocrysts in some samples. The fine-grained, 0.125 to 0.25 mm, subhedral orthopyroxene phenocrysts are biaxial negative and have a 2V ranging from about 60 to 90°. These optical properties suggest that the orthopyroxene is hypersthene (Deer and others, 1966, p. 112). Very fine-grained, less than 0.125 mm, pigeonite is identified by its low 2V (less than 30°), and its moderately low birefringence. Magnetite occurs throughout these lavas as fine-grained, granular phenocrysts.

Two varieties of plagioclase phenocrysts characterize the Geode Creek suite. The first plagioclase habit consists of fine-grained, less than 0.50 mm and averaging 0.25 mm to 0.125 mm, euhedral, lath-shaped pheoncrysts. These laths commonly display albite or combined Carlsbad-albite twins. As determined by the centered bisectrix method described by Moorhouse (1959, p. 58), the An-content of these fine-grained plagioclase phenocrysts ranges from An_{23} to An_{65}. However, as illustrated in Figure 3 the dominant composition is An_{45}. Some of these plagioclase grains display a very subtle normal zoning which is too fine-grained to measure precisely. In general, the laths are randomly oriented, and comprise 10 to 35 percent of the phenocryst assemblage.

The second plagioclase variety has a distinctive appearance, consisting of coarse grains averaging 1.25 to 1.0 mm, but measuring as much as 2.5 mm in length. These crystals contain anhedral to subround, inclusion-filled or sieved cores, and thin, 0.062 to 0.25 mm, inclusion-free, clear rims. Reverse zoning is quite pronounced in most of these grains. As measured by the centered bisectrix method, the cores range in composition from An_{22} to An_{65}, whereas the rims vary from $An_{28}$to An_{60} (Figures 4a and 4b graph the core and rim An-content distribution). The greatest contrast between rim and core composition occurs in sample #623-1a in which one grain has an An_{38} core and an An_{58} rim.

The exterior shape of these coarser plagioclase phenocrysts varies from embayed to euhedral. Although the sieved cores are commonly subrounded to anhedral, a euhedral outline is restored to most of these phenocrysts by growth of the clear rim around the core. In some instances, however, these clear rims are moderately to strongly embayed by the groundmass, or by the small, lath-shaped phenocrysts as shown in Plate 1. Some grains also contain fine-grained, irregular

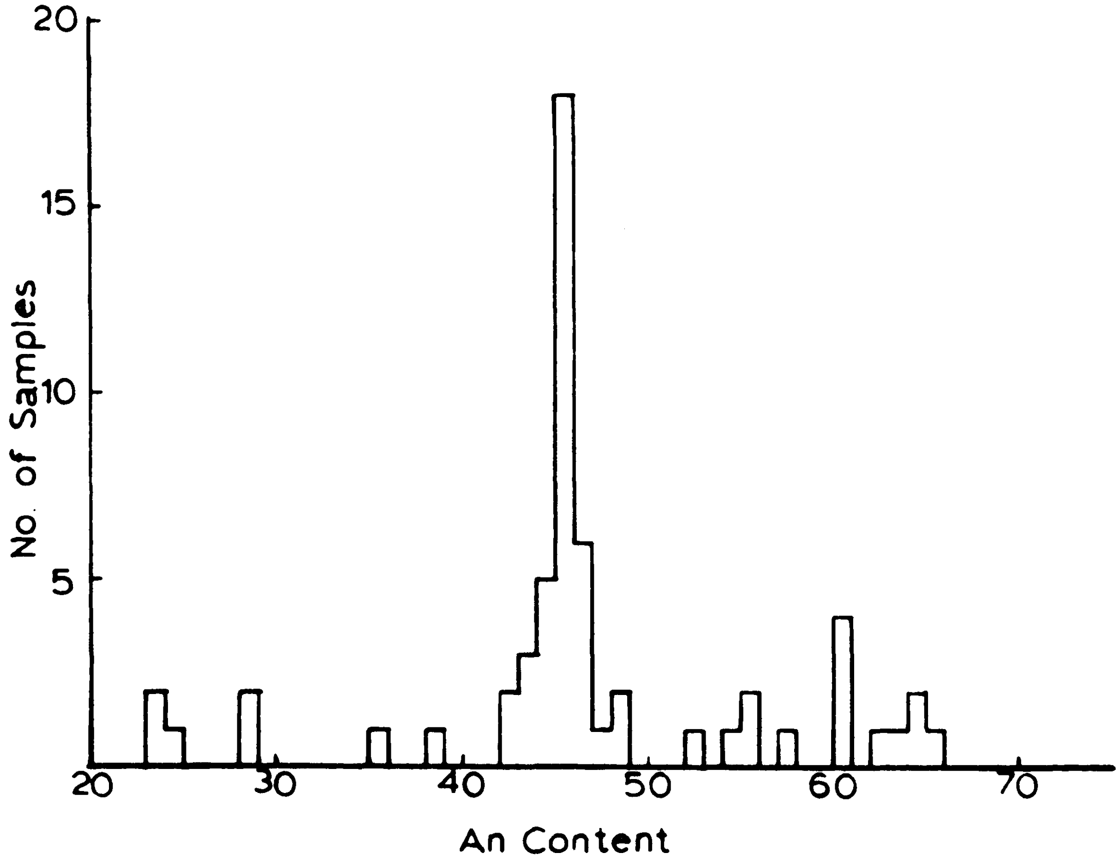

Figure 3. An-content of the Geode Creek lath-shaped plagioclase phenocrysts.

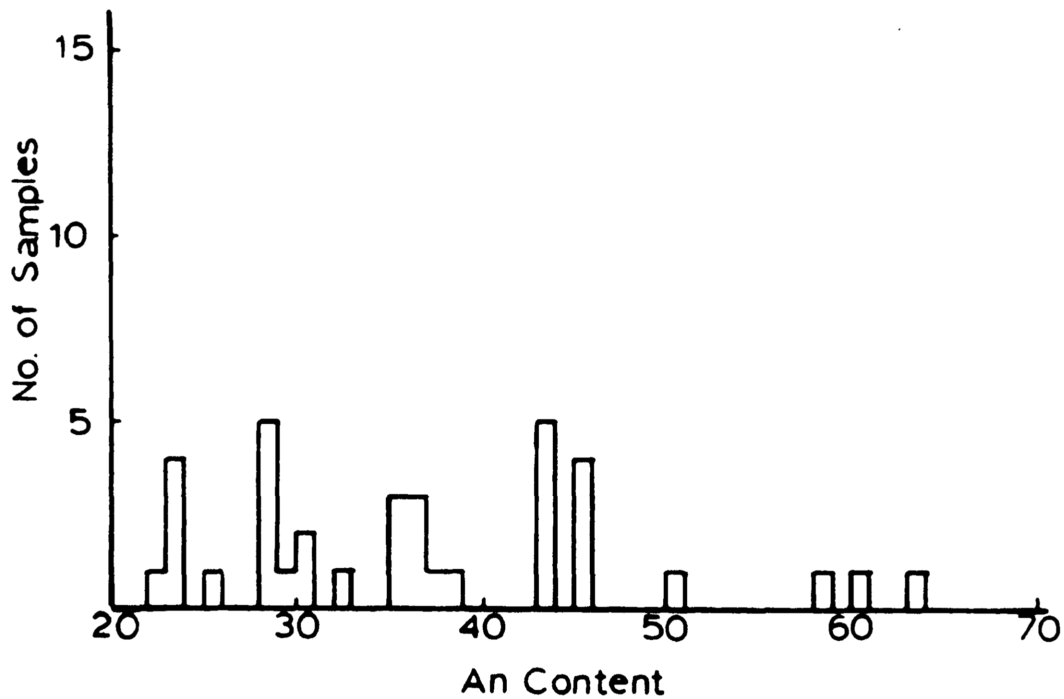

Figure 4a. An-content of the inclusion-filled cores of the Geode Creek plagioclase xenocrysts.

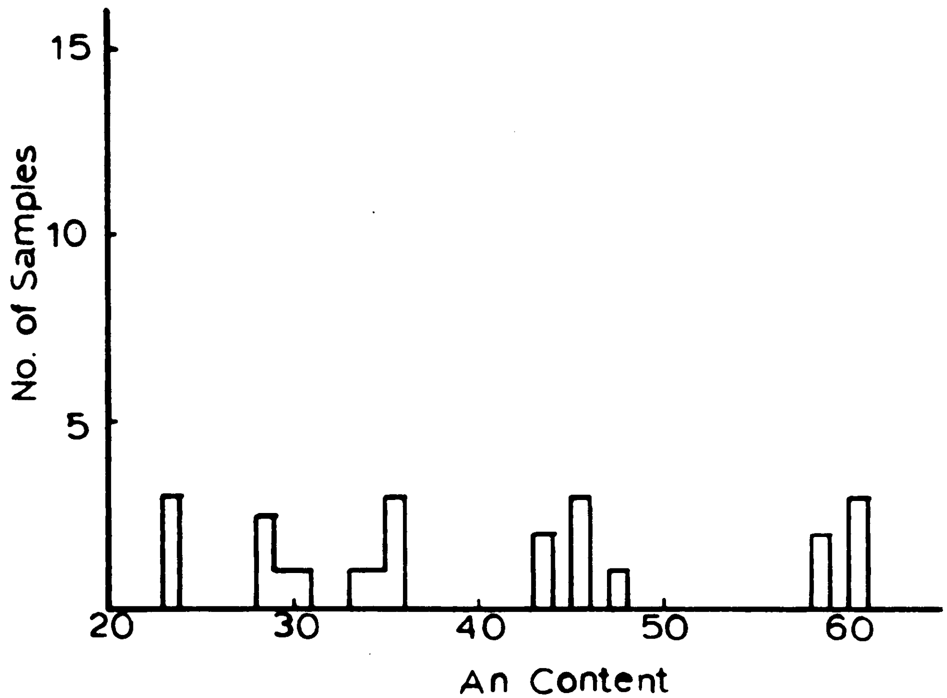

Figure 4b. An-content of the clear rims of the Geode Creek plagioclase xenocrysts.

inclusion-free cores with An-contents identical to that of the surrounding sieved portion.

The inclusions in the plagioclase cores consist of very fine grains tentatively identified as magnetite, orthopyroxene, augite and blebs of glass with a refractive index less than that of the surrounding feldspar. In some grains these inclusions have a strong crystallographic orientation within the plagioclase crystal, forming a reticulate network reminiscent of some sulfide exsolution textures. In addition to the tiny, monomineralllic inclusions, a few of these large plagioclase phenocrysts contain inclusions of fine-grained basalt. As shown in Plate 1 the texture and mineralogy of these basaltic inclusions is nearly identical to that of the basaltic groundmass of the lava as a whole. Most of these large plagioclase phenocrysts display albite or combined Carlsbad-albite twins. These coarse plagioclase phenocrysts comprise up to 10 to 15 percent of the Geode Creek lavas.

Groundmass Mineralogy

In all of the samples studied, the groundmass consists of plagioclase microlites, granular pyroxene and magnetite microphenocrysts, and variable amounts of black glass. The groundmass texture ranges from felty to sub-trachytic. As indicated in Table 1, the groundmass comprises 40 to 75 percent of these lavas.

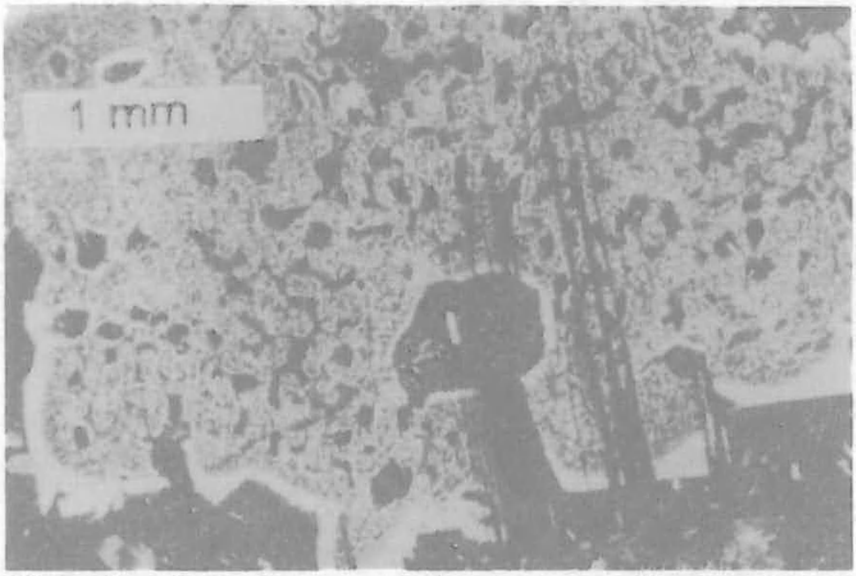

Plate 1. Photomicrograph of a coarse-grained, embayed inclusion-filled Geode Creek plagioclase xenocryst. Note the basaltic inclusion within this grain.

Plate 2. Photomicrograph of a fairly intact quartz xenocryst surrounded by a fine-grained pyroxene reaction rim from a Geode Creek lava.

Quartz and Alkali-Feldspar Grains

As listed on Table 1, many of the Geode Creek lavas contain minor quartz and alkali feldspar. These minerals occur as fine to very fine-grained crystals that are commonly, but not always, rimmed by an aggregate of fine-grained, granular pyroxenes. These rims consist dominantly of augite but may contain subordinate pigeonite and orthopyroxene.

The size and shape of these quartz grains is variable, ranging from comparatively coarse, up to 0.50 mm, subround grains, to very fine-grained fragments. The surrounding pyroxene coronas average 0.50 mm in diameter. For example, Plate 2 shows a subround quartz grain that is readily identifiable as a uniaxial positive mineral. On the other end of the spectrum, Plate 3 shows a pyroxene ring surrounding several very fine-grained fragments of quartz. The severely embayed quartz grain illustrated in Plate 4 represents a textural intermediate between the round, intact quartz grain and the fine quartz fragments discussed above.

Alkali feldspar grains were identified in only two samples. They display the same variability of textures as the quartz grains, ranging from fragmentary granules to well preserved grains. Plate 5 illustrates a fairly intact alkali feldspar grain rimmed by pyroxene.

In many of the quartz-bearing samples, and in a few quartz-free samples, subround aggregates of fine-grained, granular pyroxene, up to 0.75 mm in diameter, are scattered throughout. The texture and mineralogy of these pyroxene clots closely resembles that observed in the pyroxene rims surrounding the quartz and alkali feldspar grains. Examples of these aggregates are shown in Plates 4 and 5. Some of these aggregates contain centers of diffuse, low birefringence material resembling quartz and alkali feldspar. It should be added that these pyroxene clots may contain quartz or alkali feldspar cores which are not exposed in the plane of the thin section.

Coarse-Grained Inclusions

Coarse-grained inclusions or xenoliths, up to 3.0 mm in length, occur in two of the samples studied. As shown in Plate 6, these coarse-grained aggregates consist of anhedral plagioclase of undetermined An-content, and orthopyroxene grains. The plagioclase in these xenoliths is noteworthy not only for its size, but it is free of inclusions in contrast to the large inclusion-ridden plagioclase phenocrysts. In addition, most of the xenolith plagioclase crystals are unzoned and untwinned. Although only two samples contain coarse-grained plagioclase-pyroxene aggregates, most samples contain a few coarse-grained, anhedral crystals of inclusion-free plagioclase, resembling those observed in the xenoliths. Coarse-grained anhedral orthopyroxene grains also occur in a few lavas.

Petrographic Interpretation

Despite the dominantly basaltic appearance and mineralogy of the Geode Creek lavas, careful petrographic inspection clearly reveals that

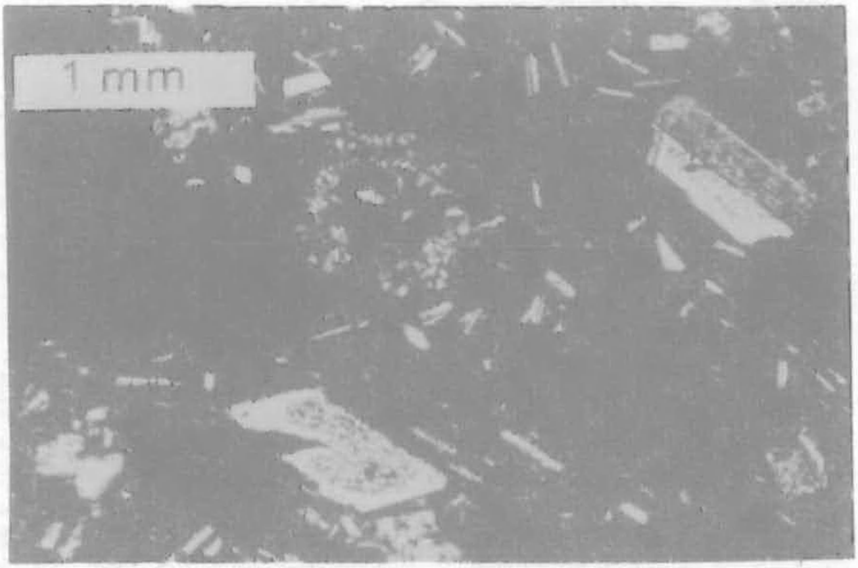

Plate 3. Photomicrograph of very fine-grained quartz fragments surrounded by a reaction rim of pyroxene from a scoriaceous Geode Creek lava. Note the inclusion-filled plagioclase grains as well.

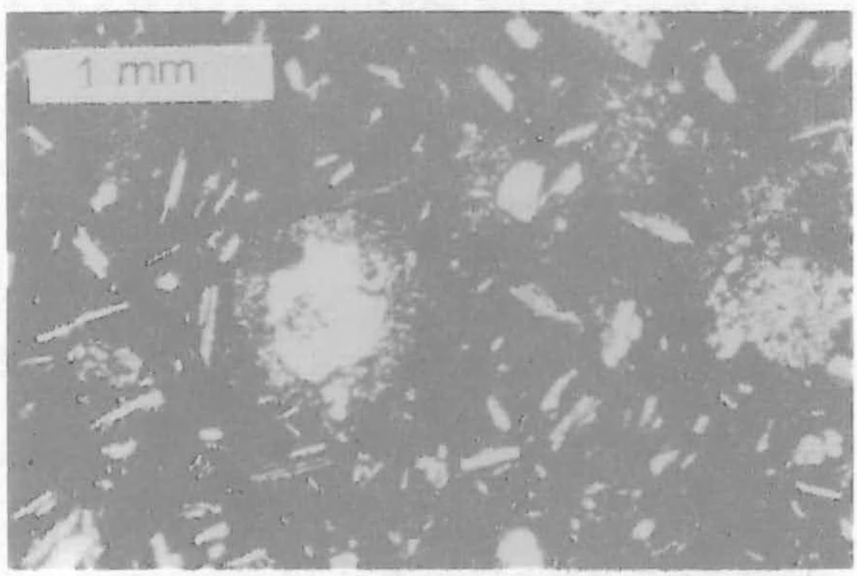

Plate 4. Photomicrograph of a severely embayed quartz xenocryst jacketed by a corona of pyroxene (center) and a fine-grained pyroxene clot (far right) from a Geode Creek lava.

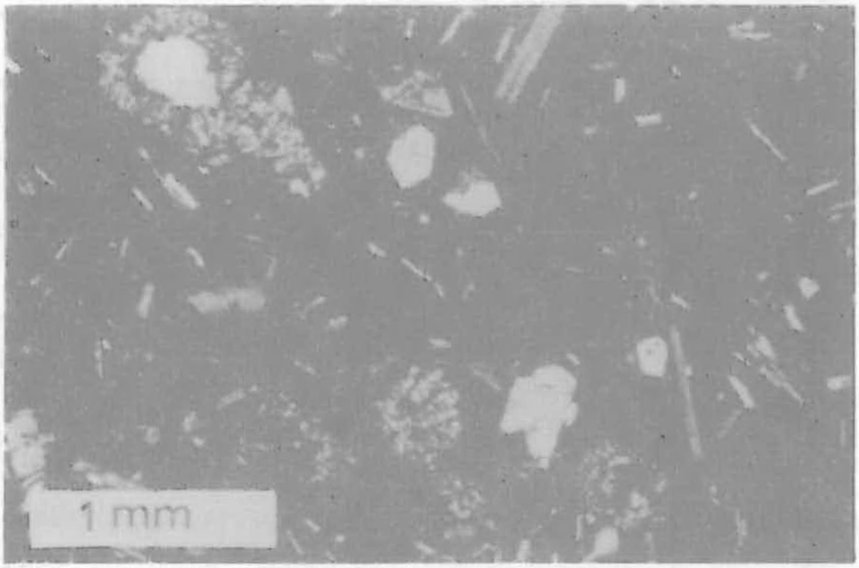

Plate 5. Photomicrograph of a Geode Creek alkali feldspar xenocryst surrounded by a pyroxene reaction rim (upper left) and a fine-grained, granular pyroxene aggregate (lower center).

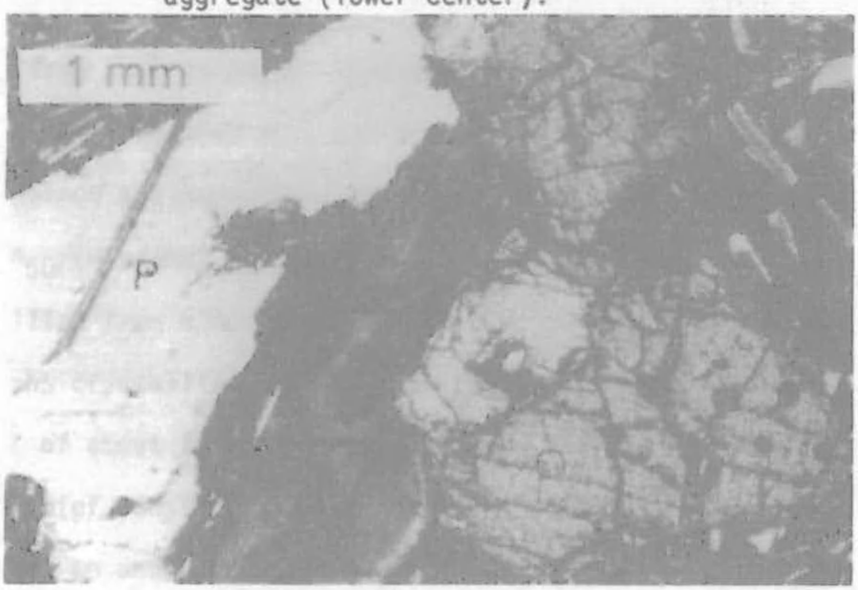

Plate 6. Photomicrograph of a coarse-grained plagioclase (P)-orthopyroxene (O) inclusion from a Geode Creek lava.

they are not normal basalts. Most notably, the unusual plagioclase textures and compositions, and the presence of quartz and alkali feldspar grains suggests that some felsic material contaminated the basaltic magma during the course of crystallization. The following is an interpretation of the observed petrographic features assuming that rhyolitic and basaltic magmas mixed prior to extrusion of the Geode Creek lavas.

One of the most obvious petrographic indications that the Geode Creek lavas are not normal basalts is the An-content of many of the plagioclase phenocrysts. Both the small, lath-shaped phenocrysts as well as the large, inclusion-filled phenocrysts have anamolously low An-contents for plagioclase crystallized from a basaltic melt.

The An-content of the small lath-shaped plagioclase phenocrysts ranges from An_{23} to An_{66}. However, sixty-four percent of the measured laths cluster between An_{42} and An_{48}; An_{45} is the average lath composition. Since the An-content of plagioclase in basalt is generally greater than An_{50} (Hyndman, 1972, p. 36), these plagioclase laths did not crystallize from a normal basaltic melt. This suggests that most of the laths crystallized from a slightly more felsic melt in which an An-content of about forty-five percent represented equilibrium.

A brief consideration of the mixing history of these lavas is necessary to understand the variable and anomalous An-content of the plagioclase phenocrysts. As rising basalt encountered rhyolite, the rhyolitic phenocrysts entered the basaltic magma and began to react. Likewise, the liquid portions of both magmas began to mix. However, thorough mixing and homogenization required sufficient mechanical stirring, and was thus not instantaneous. During this period of homogenization, the melt phase gradually evolved from a dominantly basaltic composition to a more felsic, hybrid composition.

The large proportion of plagioclase laths with An-contents near forty-five percent, suggests that these laths crystallized in equilibrium from the completely mixed hybrid melt phase. On the other hand, those plagioclase laths with An-contents greater than fifty percent probably crystallized from an average basaltic liquid, and may thus represent plagioclase phenocrysts present in the basalt prior to mixing. In contrast, the small proportion of laths more sodic than An_{42} may be phenocrysts inherited from the rhyolite, that for some reason did not react with the surrounding hybrid melt.

The large, inclusion-filled plagioclase phenocrysts are one of the most visually striking elements of the Geode Creek suite. The subround to embayed shapes of the more sodic cores suggests disequilibrium with the surrounding melt. Eighty-nine percent of the measured cores have an An-content less than An_{50}. These low An-contents indicate that these phenocrysts did not crystallize in equilibrium from a basaltic melt. The resorbed outlines of the sieved cores and some of the clear rims provides additional evidence of disequilibrium.

Plagioclase compositions in granitic rocks generally range from An_{20-35} in more sodic varieties, to An_{30-45} in more calcic types (Hyndman, 1972, p. 136-7). Thus many of the plagioclase cores fall within the range of compositions common to granitic, and by analogy rhyolitic magmas. This suggests that at least some of these sodic plagioclase cores crystallized from a magma of approximately rhyolitic composition, and that they were added to the Geode Creek lavas during mixing of rhyolite with basalt. They can thus be regarded as rhyolitic xenocrysts.

It must be noted, however, that there is a very large spread of plagioclase core compositions, ranging from An_{23} to An_{64}. Clearly those cores more calcic than An_{45} could not have formed in a rhyolitic melt, and must have crystallized in equilibrium from a more mafic magma. Since plagioclase forms a complete solid solution series, some of the originally sodic cores may have reacted with the more mafic, hybrid liquid into which they were mixed. These initially sodic compositions were transformed into calcic compositions in equilibrium with the surrounding melt.

However, this solid solution reaction of sodic plagioclase xenocrysts to more calcic compositions is complicated by the constantly changing composition of the melt phase. As mixing progressed, the originally mafic melt became more and more felsic as rhyolite continued to homogenize with the basalt. Thus the plagioclase in equilibrium with this melt evolved from an initially calcic composition to a more sodic one. In this manner, the most calcic plagioclase cores represent those xenocrysts incorporated during the early stages of mixing into a largely uncontaminated, poorly mixed basaltic magma. Thse calcic cores crystallized in approximate equilibrium from a mafic melt. As the melt became more felsic during the more advanced stages of mixing, less calcic plagioclase crystallized in equilibrium from the well-mixed, hybrid melt. Core compositions of An_{30-45} formed in equilibrium from this melt.

As noted above, the average plagioclase lath composition of An_{45} represents the plagioclase composition in equilibrium with the thoroughly mixed, hybrid melt. Thus it is not surprising that over fifty-four percent of the plagioclase cores measured have intermediate An-contents that crystallized in equilibrium or nearly in equilibrium with the completely homogenized hybrid melt. Those core compositions less than An_{30} represent rhyolitic xenocrysts that did not react to any significant extent with the surrounding more mafic melt. Thus they approximate some of the original rhyolite plagioclase compositions. In this manner, an entire gamut of plagioclase compositions form during contamination of basalt by rhyolite.

In summary, then, the sieved plagioclase cores originally formed as phenocrysts in a rhyolitic magma. These sodic crystals were subjected to varying degrees of resorbtion and solid solution reaction as they equilibrated with a more mafic melt. These cores are filled with tiny inclusions of augite, orthopyroxene, magnetite and glass. The texture and composition of these inclusions is nearly identical to that of the groundmass. Thus it appears that minute portions of groundmass crystallized within the plagioclase cores. The presence of inclusions in these cores is readily explained by considering the relatively low equilibrium temperature of these sodic xenocrysts in contrast to the higher temperature of the mafic melt into which they were mixed. Assuming initial xenocryst compositions of An_{22-30}, corresponding to the most sodic cores, these crystals started to melt when they were added to the hotter basaltic liquid. Melting occurred preferrentially along certain crystallographic directions, producing oriented blebs of sodic plagioclase glass. The pyroxene, magnetite-bearing magma penetrated the xenocrysts along these partially melted crystallographic sites, locally replacing the plagioclase. In this manner, the presence of oriented glass, pyroxene and magnetite inclusions is due to partial melting of the sodic plagioclase xenocrysts upon encountering the hotter basalt. Similar plagioclase textures are described for the San Juan volcanics (Larsen and others, 1938) and Paricutin (Wiscox, 1954).

The clear plagioclase rims surrounding the sieved plagioclase cores are consistently more calcic than the enclosed cores. They are not, however, as calcic as normal basaltic plagioclase, since seventy-eight percent of the measured rims have an An-content of less than fifty percent. This suggests that the calcic rims formed from a contaminated basaltic magma. Analogous to the variety of core compositions, the wide range in rim compositions reflects the changing nature of the surrounding melt. Although the clear rim portions of the large plagioclase phenocrysts initially formed as euhedral growths around the resorbed sodic cores, these rims are commonly embayed by the groundmass or by the small lath-shaped plagioclase phenocrysts. This suggests further disequilibrium and reaction between the rim and surrounding hybrid melt. This is not surprising since sixty-one percent of the rims have compositions more sodic than An_{45}, the plagioclase composition in equilibrium with the thoroughly homogenized hybrid melt.

The quartz and alkali-feldspar grains rimmed by pyroxene provide additional clear evidence that the Geode Creek lavas are abnormal basalts. However, these felsic crystals are not present in every sample examined. In addition, their presence is easily overlooked in many of the samples which contain only very fine-grained quartz and alkali feldspar fragments. Like the sieved cores of the large plagioclase grains, these quartz and alkali feldspar crystals are xenocrysts inherited from rhyolite. In one anomalous sample, 623-2a, quartz grains lack pyroxene rims. However, in all of the other samples, well developed pyroxene coronas formed as a result of reaction between the felsic xenocrysts with the more mafic melt.

Application of Bowen's (1928) principles of magmatic reaction elucidate this process. A basaltic liquid can melt any felsic inclusion, thereby modifying the liquid composition towards that of the inclusion. However, this dissolution requires additional heat. Since crystallization liberates energy as heat of crystallization, precipitation of the phase or phases with which the basalt is saturated can supply the extra heat needed to melt an inclusion. Bowen maintains that the amount of the inclusion melted must approximately equal the amount of crystallization of the saturated phase (p. 187). This reaction continues until all the liquid is consumed or until the inclusion is totally melted (p. 197). However, quick cooling of the magma commonly prevents this reaction from reaching completion. The resulting rock thus contains felsic inclusions surrounded by mafic reaction rims (p. 58).

The pyroxene-rimmed quartz and alkali feldspar grains in the Geode Creek lavas present a clear picture of this type of magmatic reaction. Incipient melting of these xenocrysts produced the observed rounded to embayed shapes. Simultaneously, pyroxene, the phase with which the basalt melt was saturated, crystallized and furnished the additional heat required to melt the felsic crystals. Not surprisingly, the size and shape of these pyroxene granules closely resembles their texture in the groundmass since they formed during the same stage of magma crystallization. The absence of plagioclase microlites from these reactions rims suggests that the melt was not saturated with plagioclase at the time of reaction between the magma and the xenocrysts. The abundant groundmass plagioclase microlites probably crystallized later.

In this manner, the quartz and alkali feldspar grains are commonly jacketed by fine-grained pyroxene coronas. As noted above, the size of the xenocrysts varies from 0.5 mm to mere fragments. This suggests that reaction between the xenocrysts and the melt reached various stages of completion. The fairly coarse, intact felsic grain shown in Plate 2 represents limited reaction, due either to rapid cooling or to an initially larger xenocryst. On the other hand, the very fine-grained felsic remnants illustrated in Plate 3 indicate nearly complete reaction. The severely embayed quartz xenocryst shown in Plate 4 is an example of an intermediate state of reaction. The round aggregates of granular pyroxene that are not visibly associated with any felsic material (Plates 4 and 5) may thus be reaction rims formed around thoroughly dissolved xenocrysts. In this manner, these pyroxene clots are ghost relics after quartz and alkali feldspar xenocrysts. These felsic ghosts comprise up to two percent of over seventy percent of the samples studied. It should be noted that these are subtle features that are hard to recognize in lavas with a microphenocryst-rich groundmass. Their abundance may thus be underestimated.

The Geode Creek felsic xenocrysts are very similar to quartz xenocrysts described in some of the Miocene-Pliocene contaminated basalts in the San Juan volcanics (Larsen and Cross, 1956) and in the quartz basalts at Cinder Cone in Lassen Peak (Finch and Anderson, 1930). It is interesting to note that in these examples, as well as in other mixed lavas discussed in the literature, mafic reaction rims around felsic xenocrysts are always pyroxene. If these reaction coronas represent the saturated phase at the time of reaction between the inclusion and the magma, then all of these mixed lavas were saturated in pyroxene at the time of contamination. Despite the abundance of pyroxene in basalts, it seems oddly fortuitous that all of these lavas were contaminated at essentially the same stage of magmatic evolution. Plagioclase is an equally common basaltic component. The absence of plagioclase reaction rims around felsic inclusions is thus puzzling. It is unlikely that plagioclase is never the saturated phase during contamination. Perhaps the growth of reaction rims is controlled in part by the relative ease of nucleation of the saturated phases; pyroxene may nucleate more readily than plagioclase.

In contrast to the phenocrysts inherited from the rhyolitic magma, the olivine, augite, pigeonite, orthopyroxene and magnetite were all present as phenocrysts in the basalt prior to mixing. Judging from their appearance these crystalline phases were little affected by the addition of the more felsic rhyolitic contaminant. This phenocryst assemblage thus crudely reveals the nature of the pre-contaminated basaltic magma. It should be noted, however, that the average Yellowstone basalt contains only plagioclase and olivine phenocrysts (Christiansen and Blank, in press). If the uncontaminated basaltic parent of the Geode Creek lavas was a typical Yellowstone basalt, then perhaps the pyroxene phenocrysts present in the lavas is an additional expression of contamination.

Although the coarse-grained clusters and solitary grains of clear, inclusion-free plagioclase and orthopyroxene do not offer direct evidence or magma mixing, they do provide an important clue to the ultimate source of rhyolitic magma in the Yellowstone area. These coarse plagioclase and orthopyroxene grains are foreign inclusions or xenoliths that formed in neither the basaltic nor the rhyolitic parents of the Geode Creek complex. Harker (1904, p. 394) defines two types of xenoliths. The first variety, an accidental xenolith, is a fragment randomly plucked from the country rock during magmatic intrusion. The second kind, a cognate xenolith, bears a genetic relationship to the surrounding host rock. The precise nature of the Geode Creek xenoliths must thus be determined.

First of all, the coarse-grained texture of these xenoliths strongly suggests that they are fragments of plutonic rocks. The plagioclase-orthopyroxene mineralogy is a distinctive assemblage reminiscent of granulite facies metamorphic rocks. Thus it appears that these inclusions may be fragments of plutonic rock, and more specifically may be plutonic rocks with granulite facies mineralogy. As such, these fragments may be either accidental xenoliths of plutonic material incorporated during intrusion, or cognate xenoliths that are somehow genetically related to the surrounding lava.

Lithologies in the Yellowstone region include Precambrian metamorphics, Paleozoic to Tertiary sedimentary rocks, early Tertiary intermediate volcanic rocks, and Quaternary bimodal volcanics. Any accidental xenoliths incorporated into the magma during intrusion must be derived from this wide spectrum of potential country rocks. The composition and texture of the observed plagioclase-orthopyroxene inclusions closely resemble a granulite facies metamorphic rock, and suggest the presence of granulite facies Precambrian basement beneath the Yellowstone area.

It remains to be seen whether these xenoliths may actually be cognate rather than accidental. If the source of the Yellowstone rhyolite magma is partially melted continental crust, these xenoliths may be unmelted remnants of the ultimate rhyolite source rock. This contention is strengthened by the fact that the metamorphic rocks in the area are among the most attractive candidates for partial melting due to their roughly granitic composition. In this manner these inclusions could be cognate xenoliths, representing the original source rock for the rhyolite magma.

CHAPTER VII

PETROGRAPHY OF THE GARDINER RIVER LAVAS

The suite of mixed basalts and rhyolites examined in this study does not vary significantly from the Gardiner River lavas described in detail by Fenner (1938) and Wilcox (1944). The following is a brief petrographic description of these lavas.

In contrast to the homogeneity of the Geode Creek lavas, the Gardiner River lavas display nearly endless textural and compositional variability. This heterogeneity is pervasive in outcrop, hand sample and thin section scale. Despite its complexity and diversity, however, the Gardiner River assemblage provides an exceptional opportunity to study magma mixing, since the relatively uncontaminated rhyolitic and basaltic parental magmas of these lavas are exposed in the complex. Thus this complex is best understood as a continuum of degrees of contamination with respect to the parental materials. With this in mind, the uncontaminated parental basalt is discussed first, followed by a description of increasingly contaminated basalt. The contaminated rhyolite is treated in the same fashion.

Uncontaminated Basalt

The uncontaminated basalt, or Cataract basalt (Wilcox, 1944) forms the basaltic end member of the Gardiner River complex. This fine-grained basalt is composed of olivine, pyroxene, magnetite and plagioclase phenocrysts, set in a groundmass of olivine, pyroxene and magnetite granules and plagioclase laths. Glomeroporphyritic clots of plagioclase, olivine and pyroxene phenocrysts are common. The plagioclase phenocrysts, which average from 0.5 to 0.75 mm in length, have an average composition of An_{70}. Wilcox (1944) reports values of An_{70-74} for these plagioclase phenocrysts.

Contaminated Basalt

The contaminated aspects of the Gardiner River basalt are immediately apparent in contrast to the subtle contamination features present in the Geode Creek lavas. All of the Gardiner River basalts examined in this study contain at least two percent alkali feldspar and quartz xenocrysts; some samples contain as much as ten percent felsic components. The quartz and alkali feldspar xenocryst content is a crude index of extent of contamination. In general, those lavas containing less than five percent xenocrysts are relatively less contaminated; whereas those lavas containing more than five percent xenocrysts are comparatively more contaminated. These xenocrysts have rounded to embayed outlines. In many of the xenocryst-rich samples, both the phenocrysts and the xenocrysts have a slightly mottled, corroded aspect. Unlike the Geode Creek felsic xenocrysts which are commonly surrounded by well developed pyroxene coronas, the vast majority of the Gardiner River felsic xenocrysts are not rimmed by pyroxene. The few observed pyroxene jackets are very fine-grained and very thin (see Plate 7). Pyroxene rims are most common in the xenocryst-poor lavas, and generally absent in the xenocryst-rich samples.

An analysis of plagioclase texture and composition further reveals the contaminated nature of these basalts. With an increasing degree of contamination, the groundmass plagioclase laths become finer-grained and more sodic. There is a strong correlation between increasing xenocryst content and decreasing An-content. The most sodic plagioclase, An_{18}, occurs in one of the most xenocryst-rich lavas. The plagioclase in the less contaminated basalts measures An_{45}. These observed values closely resemble Fenner's (1938) data.

In contrast to the groundmass plagioclase laths, the coarser plagioclase phenocrysts remain largely unaffected by the addition of felsic material. These plagioclase grains retain their calcic composition. Most of the mafic phenocrysts likewise appear unaltered by the contaminating rhyolite. However, in the more contaminated basalts, some of the mafic phenocrysts have started to disaggregate and disintegrate.

Like the Geode Creek lavas, the Gardiner River basalts also contain fairly coarse-grained, inclusion-filled plagioclase grains. However, these are quite rare in the Gardiner River lavas in comparison to their abundance in the Geode Creek suite.

Comparison of the Gardiner River Basalts and the Geode River Lavas

The basaltic portions of the Gardiner River Complex closely resemble the Geode Creek lavas. Both assemblages formed by the addition of a

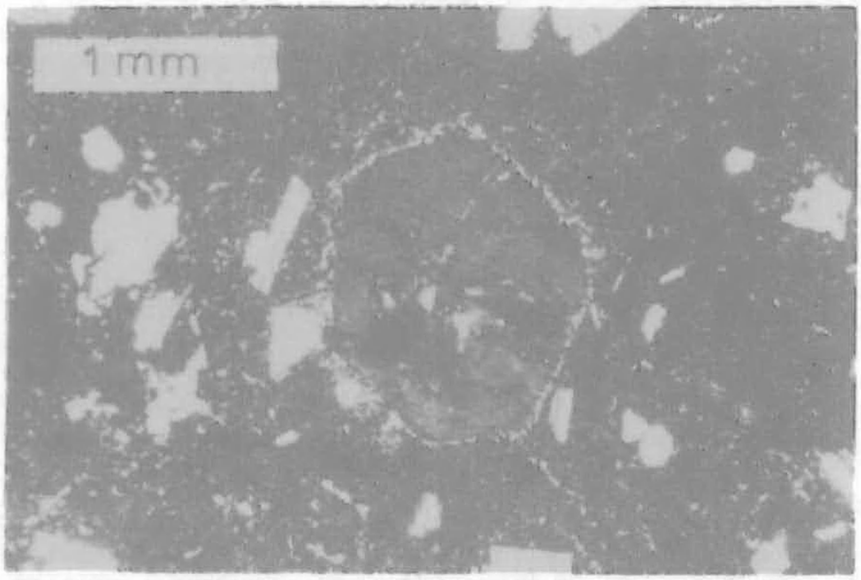

Plate 7. Photomicrograph of a quartz xenocryst surrounded by a very thin, fine-grained pyroxene reaction rim from a basaltic portion of a Gardiner River lava.

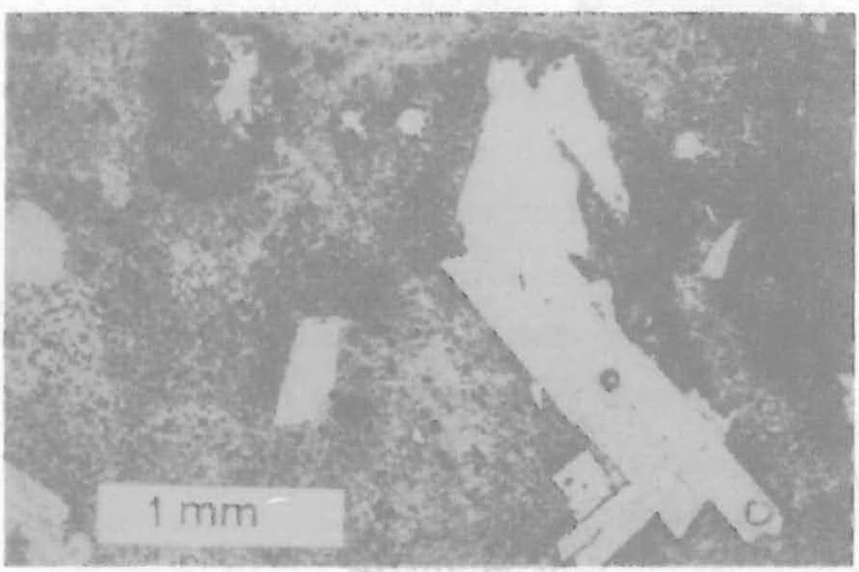

Plate 8. Photomicrograph of basaltic inclusions of various size and shape in a contaminated rhyolitic portion of the Gardiner River lavas.

rhyolitic magma to a basaltic magma prior to eruption. However, there are two significant differences between the two complexes. First, the Gardiner River basalts are much more contaminated than the Geode Creek basalts. Felsic xenocrysts never comprise more than two percent of the Geode Creek mineralogy, whereas they form two to ten percent of the Gardiner River basalts. Second, the Gardiner River assemblage cooled quickly after mixing began, thus preventing significant reaction between these xenocrysts and the surrounding mafic melt. In contrast, contamination of the Geode Creek basalts was followed by a relatively long period of mixing and homogenization, allowing for more complete magmatic reactions.

The pyroxene rims around the felsic xenocrysts furnish a convenient vehicle for studying both the degree of contamination and the post-contamination cooling history. Pyroxene rims around felsic xenocrysts are present only in the less contaminated lavas, those examples containing less than five percent quartz and alkali feldspar. The absence of these pyroxene coronas from the more contaminated samples suggests that the compositional contrast between the silicic grains and the surrounding melt was insufficient to warrant immediate reaction. This implies a relatively felsic, highly contaminated, hybrid liquid. In addition, the very fine-grained, poorly developed nature of the pyroxene rims in the less contaminated lavas indicates that reaction between the felsic xenoliths and the surrounding more mafic melt was quite limited. Presumably this incomplete reaction is attributable to rapid cooling shortly after mixing. The inhomogeneous, poorly-mixed aspect of the Gardiner River complex as a whole offers additional evidence that mixing in this complex was restricted, perhaps due to rapid cooling.

Uncontaminated Rhyolite

The uncontaminated rhyolitic component of the Gardiner River Complex, the Lodgepole Rhyolite (Wilcox, 1944) contains rounded to embayed phenocrysts of quartz, cristobalite, orthoclase, sanidine and sodic plagioclase, ranging in size from 0.25 to 2.0 mm. The rhyolitic groundmass varies from a holocrystalline, very fine-grained intergrowth of quartz and feldspar to a holohyalline mixture of glass and spherulitic devitrified glass. The glassy variety is strongly flow banded and contains abundant crystallites. These glassy and crystalline groundmass textures are commonly interlayered.

Contaminated Rhyolite

The contaminated nature of the Gardiner River rhyolites is immediately apparent both in thin section and in hand sample. Basaltic xenoliths of various size and shape are scattered throughout these rhyolitic lavas, attesting to the large-scale contamination of rhyolite by basalt. The degree of contamination is best measured by the relative proportion of these basaltic inclusions. In the less contaminated rhyolites, the basaltic fragments remain fairly small, and comprise a small proportion of the whole rock. The more contaminated rhyolites, however, may contain up to fifty percent basaltic material. At this point the distinction between a contaminated rhyolite and a contaminated basalt loses its importance.

The basaltic xenoliths range from subround to extremely irregular and embayed. Basaltic debris, in the form of mafic phenocrysts surrounded by basaltic groundmass, commonly appears as remnants strewn from nearby basaltic inclusions. Basaltic phenocrysts are rarely observed without at least a thin veneer of basaltic groundmass. Plate 8 illustrates the diverse nature of these basaltic inclusions. Most of the basaltic fragments are actually contaminated basalt and contain felsic xeno-cyrsts.

In response to increasing contamination, the rhyolite phenocrysts become more embayed; many develop internal cracks as well. In the highly contaminated rhyolites, those containing a large proportion of basaltic material, very thin pyroxene rims may form around the felsic phenocrysts.

Comparison of Contaminated Rhyolites and Contaminated Basalts

Both the Geode Creek assemblage and the Gardiner River basaltic lavas are examples of basalt contaminated by rhyolite. The rhyolitic portions of the Gardiner River complex, however, offer an excellent opportunity to study another aspect of magma mixing, namely contamination of rhyolite by basalt.

An obvious difference between the two processes is the preservation of basaltic xenoliths in contaminated rhyolites, and the absence of rhyolitic xenoliths in contaminated basalts. Rhyolitic groundmass is never observed in contaminated basalts; only rhyolitic phenocrysts persist as felsic xenocrysts. However, mafic phenocrysts surrounded by basaltic groundmass are abundant in contaminated rhyolites. This difference is readily explained by considering the contrasting crystallization temperatures of basalt and rhyolite. At surface pressures, basalt crystallizes at 1100° C (Hyndman, 1972, p. 174); rhyolite remains liquid at a temperature of about 900° C (Hyndman, 1972, p. 70). As discussed above, the liquid portions of a rhyolitic contaminant readily mix with basaltic melt, forming a hybrid, intermediate-composition melt. On the other hand, cooler rhyolitic liquid cannot assimilate additions of basalt. In fact, basaltic melts may be slightly chilled against rhyolite magmas. Walker and Skelhorn (1966) and Blake and others (1965) cite chilled basaltic xenoliths in British and Icelandic mixed lavas. It should be noted, however, that chilled basaltic margins are not clearly observed in the Gardiner River lavas. In this manner, basalt is commonly preserved as xenoliths in contaminated rhyolites. A contaminated rhyolite is thus easily recognized by these telltale basaltic xenoliths. In contrast, contaminated basalts are difficult to identify since they lack rhyolitic xenoliths and may contain only poorly preserved felsic xenocrysts.

Once again a consideration of Bowen's (1928) principles of magmatic reaction clarifies these processes. A rhyolitic magma is supersaturated with basaltic components. Thus a rhyolitic liquid cannot dissolve a basaltic inclusion, it can only react with it and "convert" it into a phase with which it is saturated (p. 193). However, minute amounts of rhyolitic liquid may penetrate the basaltic inclusion, thereby increasing the inclusion's volume and facilitating its distintegration. As the basaltic fragment is gradually modified by the rhyolite, portions of the inclusion are cast into the surrounding liquid (p. 188). Plate 8 illustrates debris strewn from a nearby xenoliths.

Coarse-Grained Inclusions

Both the basaltic and the rhyolitic portions of the Gardiner River lavas contain coarse-grained fragments, or xenoliths of plutonic country rock. Some of these inclusions are plagioclase-pyroxene aggregates that closely resemble the proposed granulite facies xenoliths observed in the Geode Creek lavas. As in the Geode Creek lavas, isolated coarse grains of plagioclase and orthopyroxene also occur in the Gardiner River assemblage. In addition, one Gardiner River sample contains an inclusion of fine-grained, sugary quartz with minor feldspar. This fragment resembles a quartz-rich aplite and provides another sample of the country rocks in the Yellowstone region.

CHAPTER VIII

SUMMARY OF THE CHARACTERISTICS OF MIXED MAGMAS

Hybrid lavas produced by the mixing of basaltic and rhyolitic magmas range from nearly homogeneous looking rocks to obviously contaminated, xenolith-bearing assemblages. The hybrid's character depends mainly upon the type of mixing and contamination involved; a basaltic melt contaminated by rhyolitic magma produces a very different assemblage than a rhyolitic magma contaminated by basaltic liquid. Of course, as basalt and rhyolite mix in roughly equal proportions. this distinction loses its importance. The Yellowstone mixed assemblages offer examples of both end members of this spectrum, and thus provide an excellent opportunity to study the process of magma mixing. The following is a summary of the characteristics common in mixed magmas based upon the features observed in the Yellowstone mixed lavas, and those features described by Eichelberger (1974, 1975) for mixed lavas in the Cascades.

Petrographic Features of Mixed Magmas

In general, when two phenocryst-bearing magmas mix, the resulting hybrid magma inherits phenocrysts from both parent magmas. These inherited phenocrysts are more appropriately termed xenocrysts. The hybrid groundmass is formed from a mixture of the liquid portions of the rhyolitic and basaltic parents, and is thus intermediate in composition. Depending upon its cooling history, the hybrid magma may also contain primary phenocrysts crystallized in equilibrium with the hybrid melt. The xenocrysts, however, are commonly in disequilibrium with the surrounding hybrid liquid, and may display disequilibrium textures such as reaction rims. The development of these disequilibrium features depends on the crystallization history of the hybrid magma. Disequilibrium reactions will be limited in those hybrid magmas erupted and quenched shortly after mixing. More importantly, reaction between xenocrysts and the surrounding melt is controlled by their respective compositions.

Following Bowen's (1928) principles of magmatic reaction, a magma is supersaturated and unable to react with those components already crystallized, and undersaturated and able to react with those components yet to be crystallized. In this manner, a rhyolitic magma is supersaturated with all but the most felsic components, whereas a basaltic magma is undersaturated with all but the most mafic components. Thus a mafic magma can chemically react with a felsic inclusion, changing its composition to one in equilibrium with the surrounding basaltic melt, thereby destroying or chemically assimilating the inclusion. On the other hand, a rhyolitic magma cannot chemically react with and assimilate a mafic inclusion. Some mechanical corrosion and distintegration of the mafic inclusion may occur, but the inclusion will always retain its identity. It should be noted that in the case of a solid solution series such as plagioclase, a silicate liquid can probably react with any previously crystallized compositions.

A more specific examination of these processes will better illustrate these principles. As a porphyritic rhyolitic magma mixes with a porphyritic basaltic melt, the liquid portions of the two magmas mix to form a new, hybrid liquid intermediate in composition between the basaltic and rhyolitic parent liquids. This liquid forms the groundmass of the new, hybrid lava. As pre-existing silicic phenocrysts are incorporated into this hybrid melt, they begin to react with the more mafic liquid. Reaction rims of pyroxene are thus common around quartz and alkali feldspar xenocrysts. For example, the quartz xenocrysts in the Geode Creek lavas and in the basaltic portions of the Gardiner River lavas are commonly fine-grained and surrounded by very fine-grained, granular pyroxene reaction rims. Subround aggregates of very fine-grained granular pyroxene with no quartz or alkali feldspar centers are present in many samples. These may represent reaction rims around silicic xenocrysts which were completely chemically assimilated by the more mafic host magma. In this manner, the evidence for rhyolitic contamination of a basalt may be quite subtle. In fact, in hand sample these lavas are commonly homogeneous, basaltic-looking rocks.

The degree of assimilation of a rhyolite by a basalt will, of course, depend upon the amount of time between mixing and eruption, the relative proportions of rhyolitic contaminant and mafic host magma, and other factors such as the degree of mechanical stirring, confining pressure and water content. Rhyolitic inclusions remain only in the most immature, incompletely mixed lavas. More thoroughly mixed hybrids will contain xenocrysts incompatible with the lava's bulk composition. These xenocrysts commonly display disequilibrium reaction rims. In the most extreme and complete stages of mixing, as equilibrium is approached, the silicic xenocrysts may be completely assimilated by the mafic magma. The former presence of the rhyolitic contaminant is identifiable only by the ghost relics of silicic xenocrysts such as the fine-grained pyroxene aggregates described for the Geode Creek lavas. Recognition of a hybrid lava that has attained this advanced degree of mixing may be very difficult and require careful examination. The Geode Creek lavas probably represent a gradation between the intermediate and advanced stages of mixing since they contain both rimmed xenocrysts and relic xenocrysts. This fairly advanced stage of mixing might also form by contaminating a large quantity of basalt magma with a proportionately smaller amount of rhyolite magma.

In contrast, recognizing a rhyolitic magma contaminated by a basalt is fairly simple since rhyolite cannot assimilate the mafic contaminant. The resulting assemblage is commonly a mafic inclusion-laden rock called a "mix-lava" by some workers (Walker and Skelhorn, 1966; and Walker, 1966). The Gardiner River lavas are a classic example of a mix lava. They closely resemble mix lavas known in Scotland (Blake and others, 1965) and Iceland (Walker and Skelhorn, 1966; and Walker, 1966). Mix lavas are spectacular in their variability due to the relative proportion of basaltic inclusions and rhyolitic host rock. In places, these lavas look predominantly rhyolitic whereas just meters away they appear dominantly basaltic. The mafic inclusions display a complete range of size and shape. Most have fine-grained chilled margins. Many have crenulated outlines, and some are wispy and drawn out. The rhyolitic portion may contain mafic xenocrysts originally formed as basaltic phenocrysts. Likewise, the basalt may have rhyolitic xenocrysts with reaction rims. Thus, on a small scale, mix lavas involve basalt contaminated by rhyolite as well as large scale contamination of rhyolite by basalt.

Thermal Parameters of Magma Mixing

Although Bowen's Reaction Series explains most of the features observed in hybrid lavas produced by mixing basaltic and rhyolitic magmas, a consideration of the contrasting physical nature of basaltic and rhyolitic magmas enhances our understanding of magma mixing. One of the most obvious and important differences between basalt and rhyolite are their thermal properties. Most petrologists agree that a dry, porphyritic basalt magma, that is a basaltic melt with no superheat, completely crystallizes at slightly less than 1100°C at atmospheric pressures (Hyndman, 1972, p. 174). Dry porphyritic rhyolite remains liquid at atmospheric pressures to a temperature of about 900°C

(Hyndman, 1972, p. 70). This difference in crystallization temperatures is sufficient to chill liquid basalt adjacent to molten rhyolite. Thus chilled basaltic margins are common in mix lavas and composite intrusives (Walker and Skelhorn, 1966; Blake and others, 1965). In addition, the quick chilling of this basalt may liberate enough heat to lower the viscosity of the adjacent rhyolite, explaining the back-veining and other fluid phenomenon observed in some mixed assemblages (Walker and Skelhorn, 1966; Blake and others, 1965). In general, rhyolitic magmas are quite viscous due to the high degree of polymerization of silica tetrahedra. However, viscosity is lowered by heating (Hyndman, 1972, p. 46, 74).

Eichelberger (1974, 1975) has proposed an alternative method of magma mixing. He contends that the young, glassy volcanics in the volcanic pile contaminate rising primary basaltic and rhyolitic melts. According to this model, the non-crystalline, glassy, groundmass components of these volcanics are readily melted by the heat from ascending magmas. As the glassy groundmass melts, it mixes with the liquid portion of the rising magma. In addition, the crystalline phenocryst constituents of the disintegrating lava are incorporated into the upwelling magma. In this manner, older perhaps consanguineous, volcanics may contaminate future melts. The resulting rocks are intermediate hybrid lavas displaying disequilibrium and contamination features presumably identical to those produced by the direct mixing of two contrasting melts.

Discussion

The preceding criteria for recognizing mixed assemblages apply only to porphyritic parental magmas. Mixing, however, may not always involve two or even one phenocryst-bearing magma. In this case, detection of magma contamination and hybridization is difficult, if not impossible, for there are no xenocrysts in the resulting hybrid. Most ascending magmas closely follow their liquidus curves and are thus porphyritic. However, it is conceivable that mixing at deeper crustal levels could involve two superheated magmas without phenocrysts. The resulting hybrid lava would be unrecognizable as such.

It should also be noted that many of the features described for mixed basalt-rhyolite assemblages commonly occur in many magmatic arc andesites as well. The abundant and varied phenocryst assemblage characteristic of these andesites is difficult to produce by normal magmatic differentiation in which all phenocryst phases crystallize in equilibrium from the surrounding melt. An alternative model involving mixing of a porphyritic mafic magma with a porphyritic felsic magma could readily produce this diverse phenocryst mineralogy (Walker and Skelhorn, 1966). Thus many arc-andesites formerly interpreted as products of normal magmatic differentiation may in fact be hybrid lavas formed by mixing of basaltic and rhyolitic melts.

A disequilibrium assemblage of phenocrysts is often ascribed to lack of equilibrium during normal magmatic differentiation due largely to insufficient time for complete reaction. However, many disequilibrium assemblages may also be produced by mixing two porphyritic magmas of contrasting composition. Magma mixing should be considered as a possible petrogenetic model for any rock containing phenocrysts in disequilibrium.

CHAPTER IX

CHEMICAL AND ISOTOPIC STUDY OF SOME YELLOWSTONE BASALTS AND RHYOLITES

The Geode Creek Lavas

In addition to the ample petrographic evidence suggesting that the Geode Creek lavas are abnormal, hybrid basalts, a chemical analysis of these lavas also reveals their contaminated nature. Table 2 lists the SiO_2, MgO, and Na_2O content for twelve samples of Geode Creek basalt. A complete oxide analysis for one sample is shown in Table 3. The average SiO_2 content for these lavas is 53.9 percent, an abnormally high value relative to nearby, contemporaneous, uncontaminated Yellowstone basalts, and to continental tholeiites in general. The Swan Lake Flat Basalts, of which the Geode Creek lavas are a member, average 50.3 percent SiO_2 (Christiansen and Blank, in press); average continental tholeiites contain 51 percent SiO_2 (Hyndman, 1972, p. 12).

Traditionally chemical data for igneous rocks are presented on a variation diagram, plotting the weight percent of the various oxides versus the weight percent of silica. The curves supposedly illustrate an oxide's behavior during differentiation from mafic to silicic compositions. Harker (1904, 1909) discusses the use of variation diagrams in studying contaminated lavas. He contends that mixed magmas have hybrid oxide curves which should plot either above or below those oxide curves for normal, uncontaminated lavas. However, this contention assumes that the contaminated magma was formed from two consanguineous liquids differentiated from the same parent. This is not the case for most contaminated lavas which are a mixture of independent, primary basaltic and primary rhyolitic melts. Isotopic analyses of the Gardiner River mixed assemblage (Christiansen and Blank, in press) and the Handkerchief Mesa mixed lavas in the San Juan Mountain volcanics (Lipman and others, 1978) suggests two separate sources of rhyolitic and basaltic magmas. A similar, independent origin of rhyolite and basalt is inferred for other mixed magmas. Therefore, the use of variation diagrams in the study of mixed basalt-rhyolite assemblages is misleading. No variation diagrams are included in this study.

Figure 5 is a plot of the SiO_2, Na_2O and MgO content of the Geode Creek lavas, recalculated on the basis of 100 percent, making it possible to show them on a triangular diagram. The contemporaneous Lava Creek Rhyolite tuff (Table 4), the Swan Lake Flat basalt (Table 5) and the Madison River basalt (Table 6) are also shown. It is immediately apparent that the Geode Creek lavas fall on a straight line between the Swan Lake Flat basalt and the Lava Creek Rhyolite tuff. This position of the Geode Creek lavas suggests that the Swan Lake Flat basalt and the Lava Creek tuff, or rocks very similar to them, approximate the end member mafic and felsic parents of the Geode Creek assemblage. If the Geode Creek lavas were not genetically related to the Swan Lake Flat basalt and the Lava Creek tuff, their position would presumably be random with respect to the Swan Lake Flat and Lava Creek lavas,

Table 2. SiO_2, MgO, and Na_2O content of the Geode Creek lavas. All analyses determined by atomic absorption by Skyline Labs., Inc., Wheat Ridge, Colorado.

Sample No.	SiO_2 (%)	MgO (%)	Na_2O (%)
GC-3	54.1	4.7	2.8
GC-622-2a	53.6	4.9	2.8
GC-622-2b	53.3	4.8	2.8
GC-622-3a	52.8	4.9	2.8
GC-622-3b	50.8	4.5	2.8
GC-622-6a	52.4	4.7	2.7
GC-623-1a	54.2	4.8	2.8
GC-623-2a	55.3	4.7	2.7
GC-623-3a	55.5	4.8	2.8
GC-623-3b	55.0	5.0	2.8
GC-624-1a	52.2	4.9	2.8
GC-624-3a	54.7	5.0	2.8

Table 3. Whole-rock chemical analysis for one sample of Geode Creek basalt. Data from Christiansen and Blank (in press)

SiO_2	54.29 (%)
Al_2O_3	15.87
FeO (Total)	9.85
MgO	5.44
CaO	8.24
Na_2O	2.85
K_2O	1.45
TiO_2	1.65
P_2O_5	0.20
MnO	0.15

Table 4. Whole-rock chemical analysis of the Lava Creek Rhyolite Tuff, Yellowstone National Park. Data from Christiansen and Blank (in press).

SiO_2	76.88	77.89	77.36	76.48	76.45	78.20	75.28	77.15	76.29	76.54	79.06	77.29
Al_2O_3	12.58	12.60	12.24	12.41	12.84	12.17	13.14	12.24	12.65	12.77	11.76	12.65
FeO (Total)	1.50	0.90	1.24	1.59	1.59	1.03	1.79	1.46	1.53	1.64	0.94	1.49
MgO	0.15	0.07	0.12		0.01		0.11	0.03	0.03	0.16	0.06	0.04
CaO	0.27	0.24	0.28	0.49	0.27	0.26	0.49	0.51	0.45	0.34	0.29	0.45
Na_2O	3.35	3.33	3.00	3.71	3.40	3.26	3.84	3.18	3.62	3.32	2.60	2.50
K_2O	5.07	4.84	5.53	5.13	5.24	4.94	5.15	5.22	5.24	5.03	5.01	5.41
TiO_2	0.14	0.10	0.13	0.13	0.13	0.10	0.16	0.18	0.16	0.14	0.11	0.11
P_2O_5	0.02	0.02	0.07	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.13	0.02
MnO	0.03	0.02	0.01	0.04	0.04	0.02	0.03	0.02	0.02	0.04		0.03

Table 5. Whole-rock chemical analysis of the Swan Lake Flat Basalts, Yellowstone National Park. Data from Christiansen and Blank (in press).

SiO_2	50.62	50.13	50.15	49.91
Al_2O_3	16.07	15.60	15.34	15.37
FeO (Total)	10.24	10.56	10.51	10.51
MgO	7.51	7.56	7.63	7.94
CaO	10.38	10.93	11.13	1.04
Na_2O	2.82	2.36	2.50	2.45
K_2O	0.45	0.47	0.44	0.42
TiO_2	1.54	1.95	1.81	1.91
P_2O_5	0.22	0.28	0.37	0.25
MnO	0.16	0.15	0.13	0.16

Table 6. Whole-rock chemical analysis of the Madison River Basalts, Yellowstone National Park. Data from Christiansen and Blank (in press).

SiO_2	48.85	51.81	47.05	48.30	52.20
Al_2O_3	16.48	15.68	15.82	15.77	15.71
FeO (Total)	12.56	11.29	14.19	13.24	10.95
MgO	6.21	6.10	6.85	6.83	6.08
CaO	9.44	8.77	9.37	9.24	8.62
Na_2O	2.98	2.95	3.22	3.31	3.04
K_2O	0.57	1.12	0.46	0.56	1.12
TiO_2	2.40	1.88	2.42	2.21	1.82
P_2O_5	0.31	0.23	0.39	0.33	0.28
MnO	0.20	0.17	0.22	0.21	0.17

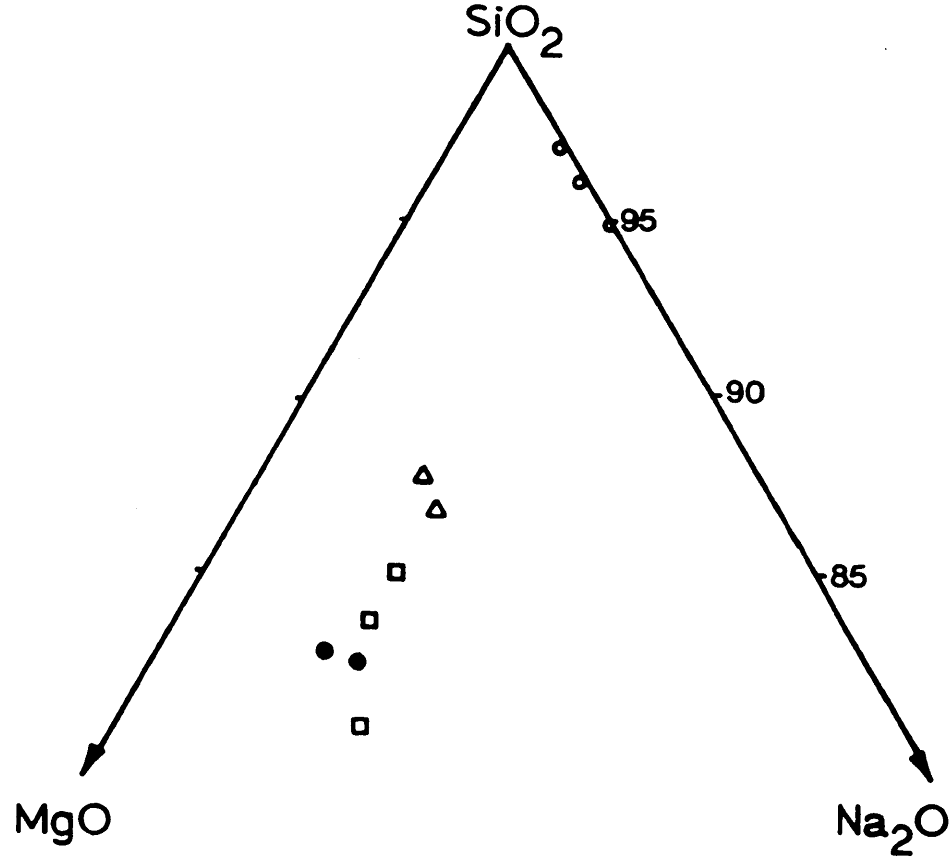

Figure 5. SiO_2-Na_2O-MgO diagram for the Lava Creek Rhyolite Tuff (o), (12 samples); the Geode Creek mixed lavas (Δ), (13 samples); the Swan Lake Flat Basalts (●), (4 samples); and the Madison River Basalts (□), (5 samples). All data have been recalculated on the basis of 100%. See Tables 2-6 for complete chemical analysis.

and they probably would not plot on a straight line between these two end members.

The Madison River basalts are more variable than the Swan Lake Flat basalts, ranging from 47 to 52 percent SiO_2 (Christiansen and Blank, in press), and their plot on the triangular diagram is correspondingly scattered. Only a portion of the Madison River basalts lie on a straight line with the Geode Creek lavas and the Lava Creek tuffs. This lack of coincidence is not surprising since the Madison River basalts are geographically removed from the Geode Creek lavas. It should be noted that the 52.20 percent SiO_2 value reported by Christiansen and Blank (in press) for one sample of Madison River basalt is anomalously high for standard Yellowstone basalts. Some of the Madison River basalts may be slightly contaminated by silicic material. This suggests that there may be other unrecognized contaminated basalts in the Yellowstone region.

The Gardiner River Complex

The gross inhomogeneity of the Gardiner River mixed lavas makes any chemical analysis of the complex a difficult task. Collection of a representative suite would require a very large volume of rock due to the large- and small-scale variability of these lavas. Chemical analyses of hand sample-size specimens serves only to attest to their chemical variability. Indeed, the analyses reported by Fenner (1938) reflect this inhomogeneity. They range from 50.5 to 75.7 percent SiO_2.

Age and Composition of the Lower Crust Beneath the Yellowstone Area

The coarse-grained plagioclase-orthopyroxene xenoliths observed in the Geode Creek and Gardiner River lavas may indicate granulite facies basement rocks underlying the Yellowstone area. Partial melting of these and similar rocks in the lower crust may have generated the Yellowstone rhyolites. Christiansen and Blank (in press) cite Sr isotope data that support this contention. The contrasting $^{87}Sr/^{86}Sr$ ratios for Yellowstone basalts and rhyolites implies derivation from different parental materials. The initial $^{87}Sr/^{86}Sr$ ratio for most Yellowstone basalts is 0.7060 $\pm$ .0005, consistent with an upper mantle source. The ratio for Yellowstone rhyolites, on the other hand, is 0.713 $\pm$ .0015, suggesting a lower continental crustal source of rhyolitic melt. On the basis of Sr and Pb isotope data, Lipman and others (1978) reach similar conclusions concerning the origin of rhyolitic and basaltic magmas in the San Juan volcanic field of Colorado.

The age and specific composition of the lower crust underlying the Yellowstone region is, however, in contention. Christiansen and Blank (in press) propose that the relatively nonradiogenic initial $^{87}Sr/^{86}Sr$ ratio for Yellowstone rhyolites precludes a Precambrian sialic source, since most Precambrian rocks in the region have fairly radiogenic initial $^{87}Sr/^{86}Sr$ ratios of 0.760 and higher. Furthermore, Christiansen and Blank (in press) interpret this lower crust as a mafic to intermediate composition pyroxene granulite to explain its nonradiogenic character.

There are several problems with Christiansen and Blank's model. First, initial $^{87}Sr/^{86}Sr$ ratiosof Precambrian rocks can vary considerably with metamorphic grade. For example, granulite facies rocks are significantly depleted in potassium, uranium, thorium and rubidium compared to amphibolite facies rocks. These lithophile elements strongly fractionate into any partial melts that may form during upper amphibolite and lower granulite facies metamorphism, and then migrate upwards to lower-grade terranes (Lambert and Heir, 1968, 1971; Hyndman and Hyndman, 1968; Lewis and Spooner, 1973). In this manner, Precambrian granulite facies metamorphic rocks may be potassium-uranium-, thorium-, and rubidium-poor and thus significantly less radiogenic than contemporaneous lower-grade metamorphic assemblages. Therefore, initial $^{87}Sr/^{86}Sr$ ratios cannot be used in age comparisons between granulite facies and lower-grade facies metamorphic rocks. Most Precambrian pyroxene granulite facies rocks have initial $^{87}Sr/^{86}Sr$ ratios ranging from 0.700 to 0.707 (Spooner and Fairbairn, 1970). The 0.760 $^{87}Sr/^{86}Sr$ value cited for Precambrian rocks in the Yellowstone region is probably a value for lower-grade assemblages. Many of the metamorphic complexes exposed in the Yellowstone vicinity consist of biotite and hornblende-rich rocks, probably representing an amphibolite facies mineralogy (Ruppel, 1972). Thus the nonradiogenic nature of the proposed Yellowstone lower crust is not due to its youthfulness, but is an expression of its higher metamorphic grade in comparison to the lower-grade metamorphic rocks exposed in the area.

Second, the initial $^{87}Sr/^{86}Sr$ ratio of the Yellowstone rhyolites does not necessarily imply a mafic or intermediate composition granulite facies source rock. This ratio could also suggest a more silicic composition granulite facies rhyolite parent. The relatively non-radiogenic nature of this source need not indicate a mafic composition. Once again, it may merely reflect the fractionation of radioactive elements from granulite facies rocks of all compositions during high-grade metamorphism.

Initial $^{87}Sr/^{86}Sr$ ratios in granulite facies rocks are not particularly sensitive to changes in granulite composition. For example, using Spooner and Fairbairn's (1970) data, twenty-eight analyzed charnockite samples have an average initial $^{87}Sr/^{86}Sr$ ratios of 0.7224. This ratio is quite variable, however, ranging from 0.7044 to 0.7695. Similarly, ten measured mafic granulites have initial $^{87}Sr/^{86}Sr$ ratios ranging from 0.7054 to 0.7430, and averaging 0.7153. In this manner, the initial $^{87}Sr/^{86}Sr$ ratio for silicic and mafic granulites overlap considerably. As such, the Sr isotope data provide no specific information concerning the composition of the Yellowstone lower crust. Based solely upon the Sr isotope data, this lower crust may be either a mafic pyroxene granulite, as suggested by Christiansen and Blank (in press), or a more silicic granulite facies rock.

A deep crustal seismic investigation of the Yellowstone area would help define the composition of the lower crust. In a study of seismic velocities in granulite facies rocks, Christensen and

Fountain (1975) demonstrate that velocities in granulites vary systematically with changes in granulite facies mineralogy. Moreover, the range measured for granulite facies rocks is similar to the variation of seismic velocities observed for the lower crust. Thus, although the lower crust is probably a granulite facies assemblage, its composition is variable.

In general, seismic velocities increase with decreasing SiO_2 content. Mafic granulites should therefore have higher seismic velocities than more felsic granulite facies rocks. Since a wide range of granulite facies mineral assemblages can have similar compressional wave velocities (V_p), the variation of granulite facies compositions is best measured by changes in shear wave velocities (V_s). Poisson's ratio (V_p/V_s) is a fairly sensitive indicator of changes in granulite facies compositions.

The presence of plagioclase-bearing granulite facies xenoliths in both the Geode Creek and the Gardiner River lavas provides permissive evidence of fairly felsic granulite facies crust at some depth beneath the Yellowstone region. Plagioclase exists only in the felsic to intermediate composition, low- to medium-pressure granulite facies. Plagioclase is unstable in the mafic, high-pressure granulite facies (Lambert and Heier, 1968, 1971). There is, of course, no assurance that these xenoliths came from the lower crust; they may represent shallower crustal compositions. Nevertheless they do attest to the presence of relatively silicic granulite facies rocks at depth.

CHAPTER X

OTHER EXAMPLES OF MIXED MAGMAS

Although the Yellowstone mixed assemblages provide an excellent opportunity to study magma mixing, further insight into this process is gained by considering other mixed complexes. Mixed lavas in the British Isles, Iceland, the San Juan Mountain volcanics of Colorado and in the Cascades resemble the Gardiner River and Geode Creek assemblages. These mixed lavas display petrographic features similar to those observed in the Yellowstone mixed lavas. With the exception of the Cascade examples, these mixed lavas formed in an environment of regional extensional tectonics, analogous to the Yellowstone setting.

Mixed Lavas in the British Isles

The British Tertiary or Hebridean igneous province extends from northwestern Scotland to northeastern Ireland. Magmatic rocks generally occur as either northwest-trending mafic dikes and dike swarms, probably representing tholeiitic and alkaline olivine flood basalt feeders, or as central intrusive complexes. Flood basalts are preserved in Skye, Mull and Ardnamurchan, Scotland and in Antrim, Ireland. Intrusive complexes outcrop in Skye, Rhum, Ardnamurchan, Mull and Arran along the western coast of Scotland, and in Carlingford, Slieve Gullion, and Mourne in Ireland (Noe-Nygaard, 1973). These central intrusives consist of ring dikes and cone sheets, commonly characterized by cauldron subsidence and caldera formation (Richey, 1961). In this manner, the British Tertiary province is structurally and petrologically similar to the Yellowstone area.

The close association of mafic and felsic magmas is common in this province. Mafic-felsic complexes include separate but neighboring intrusives of gabbro-dolerite and granophyre in Skye and Mull, net-veined complexes of gabbro-dolerite riddled with an intersecting network of granophyre veinlets in Rhum and Ardnamurchan, and composite dikes and sills in Skye and Arran. Most of these features indicate simultaneous eruption of mafic and silicic magmas (Wells, 1954). The intimate association of these two magmas in intrusive bodies commonly forms a hybrid rock of intermediate composition due to the nearly complete mixing of mafic and silicic magmas (Stewart, 1965).

Composite dikes and sills are quite common, not only throughout the British Tertiary province, but in Iceland as well. They exhibit many features common in other examples of mixed basalt-rhyolite associations, especially in the Gardiner River mixed lavas. Composite dikes and sills consist of thin basaltic margins and a much thicker rhyolitic center. The silicic core usually contains inclusions of chilled basalt which was still plastic or partially molten at the time of incorporation. The basaltic margins are chilled adjacent to the rhyolite, and commonly contain xenocrysts of rhyolitic affinity

(Walker, 1966). In addition, the rhyolitic component adjacent to the basaltic margins may be hybridized (Walker and Skelhorn, 1966). For example, the composite sill at Rudh'an Eireannaich in Skye, Scotland, is composed of upper and lower basaltic margins, a hybrid zone inward from each basaltic margin, and a felsite center. This hybrid zone is a contaminated basalt containing xenocrysts of albite, orthoclase and quartz inherited from the felsite (Buist, 1959). Pyroxene reaction rims commonly envelop the quartz xenocrysts in composite intrusives (Srirama Rao, 1959). These xenocrysts closely resemble the silicic xenocrysts observed in the Geode Creek and Gardiner River contaminated basalts.

Most workers, including Walker (1966), Walker and Skelhorn (1966), Blake and others (1965), Stewart (1965), and Wells (1954) conclude that composite dikes form by simultaneous or essentially simultaneous intrusion of basaltic and rhyolitic magmas. In some cases rhyolite was injected into hot, partially crystalline basalt (Walker and Skelhorn, 1966). The semi-molten state of the basalt explains the plastic appearance of basaltic inclusions within the rhyolitic centers of composite intrusives. These basaltic inclusions as well as the basaltic margins adjacent to the rhyolite centers are commonly chilled, suggesting simultaneous injection of basaltic and rhyolitic liquids. Basaltic magmas crystallize at about 1200° to 1000° C, whereas rhyolitic magmas remain molten until 900° to 700°C. Thus, liquid or partially liquid basalt can be chilled by molten or partially molten rhyolite (Walker and Skelhorn, 1966). Pursuing this logic, rhyolitic magma may be heated as it intrudes hotter basalt, thereby reducing the rhyolite's viscosity. The complex back-veining or net-veining of some mafic intrusives by rhyolitic veinlets may be explained by the decreased rhyolite viscosity due to heat transfer from the basalt (Wells, 1954; Blake and others, 1965; and Walker and Skelhorn, 1966). The xenocryst-bearing basaltic inclusions and the fluid-looking, "marble cake" appearance of the Gardiner River lavas are analogous to some of the features described for composite dikes and sills. Hawkes (1945) even proposed that the Gardiner River complex is a composite dike similar to those in Scotland and Iceland. However, the margins of the Gardiner River assemblage are rhyolitic rather than basaltic. Thus, field relations do not support Hawke's contention.

The Western Red Hills intrusive complex in the Isle of Skye provide a striking example of contaminated and hybrid lavas produced by magma mixing. These intrusives which were first studied by Harker at the turn of the century, consist of two hybrid rocks locally called marcoite and glamaigite. Marscoite is a homogeneous intrusive composed of calcic plagioclase, potash feldspar and quartz xenocrysts, set in an intermediate groundmass of plagioclase, potash feldspar, quartz, and hornblende. Glamaigite is compositionally equivalent to marscoite, having the same xenocryst assemblage as marscoite. Glamaigite, however, is not homogeneous, containing diffuse light and dark patches (Wager and others, 1965). According to Wager and others (1965), both marscoite and glamaigite formed by the mechanical mixing of a porphyritic, calcic plagioclase-bearing mafic lava, and a more felsic, quartz and potash feldspar-bearing magma. Vigorous mechanical stirring and complete mixing of the two magmas produced the homogeneous marscoite. In contrast, glamaigite formed by incomplete mixing of the two parent liquids.

Wager and others (1965) compare the Red Hills complex to the Gardiner River assemblage in Yellowstone Park. They propose that like the Red Hills complex, the Gardiner River lavas formed by the comingling of porphyritic mafic and felsic magmas. Extending this comparison, the thoroughly mixed marscoite is analogous to the homogeneous Geode Creek lavas; whereas the poorly mixed glamaigite resembles the heterogeneous Gardiner River lavas. Wager and others (1965) contend that mixing in the Red Hills complex occurred in a small, high level magma chamber under conditions of low P_{H_2O}. Drusy cavities in the glamaigite and marscoite, and perthitic feldspars attest to a low P_{H_2O} environment. Mixing may have taken place along the contact between adjacent basaltic and rhyolitic convecting magmas. The proposed shallow, dry conditions of magma mixing in the Red Hills complex is similar to the environment suggested for magma mixing in general.

Mixed Lavas in Iceland

The intimate association of basaltic and rhyolitic magmas in Iceland inspired Bunsen's (1851) theory of primary basaltic and rhyolitic magmas, and hybrid intermediate composition magmas. Like the British Tertiary province, Tertiary volcanism in Iceland is composed dominantly of tholeiitic and alkaline olivine flood basalts related to fissure dikes, dike swarms and central volcanoes (Noe-Nygaard, 1973).

Silicic volcanics comprise up to ten percent of the entire volcanic pile of eastern Iceland. These rhyolitic rocks commonly occur in the cores of central volcanoes where they are closely associated with mafic and hybrid intermediate rocks (Noe-Nygaard, 1973). The Breiddalur and Thingmuli central volcanoes are well known examples of this association. The interaction of basaltic and rhyolitic magmas has produced composite dikes and sills, composite lava flows, mixed lavas, mixed pyroclastics, net-veined intrusive complexes, and homogeneous or nearly homogeneous hybrids of intermediate composition (Walker, 1966). Silicic-mafic associations unrelated to central volcanoes include the gabbro-granophyre intrusions on Austurhorn and Vesturhorn. As in the British Isles, magmatism and magma mixing in Iceland apparently occur at shallow levels. Cone sheets and ring dikes in western Iceland suggest magma chambers at depths of only 2 to 3 km (Noe-Nygaard, 1973). Although mixed lavas in Iceland are not voluminous, they are widespread. Walker (1966) contends that mixing of basaltic and rhyolitic magmas in Iceland was inevitable due to the great volumes of mafic and felsic magmas erupted over a long time span. This observation is applicable to any bimodal volcanic province; mixed lavas should be common.

Tectonic Setting of Iceland and the British Isles

The Tertiary to Recent volcanics in Iceland and the British Isles are part of the North Atlantic igneous province, a huge area of flood basalts including the basalts on Baffin Island, west and east Greenland, the islands of Jan Mayen, Iceland and the Faeroes, and northwestern Scotland and northeastern Ireland. These basalts are directly related to the rifting of the Laurasian super-continent, and the formation of the present Atlantic ocean, beginning perhaps as early as mid-Mesozoic time (Noe-Nygaard, 1973). The island of Iceland sits atop the Mid-Atlantic Ridge. Clearly volcanism and rifting in Iceland are controlled by the extensional tectonic environment associated with the Mid-Atlantic spreading center (Noe-Nygaard, 1973). By analogy, the British basalts and their associated rhyolitic rocks probably formed in an extensional, rift zone environment as well.

The presence of rhyolite in Iceland, an oceanic ridge island, raises many questions concerning the origin of rhyolite. Most of the islands of the Mid-Atlantic Ridge are not composed of sialic material (Walker, 1966). In a study of the Thingmuli volcano Carmichael (1964), concludes that rhyolite formed by fractionation from a basaltic parent magma. In contrast, Walker (1966) contends that fractionation could not have produced the volume of rhyolite known in Iceland. Moreover, the scarcity of intermediate rocks, many of which are hybrid in origin, limits the importance of magmatic differentiation in the origin of

Iceland rhyolites. Walker proposes that the Icelandic rhyolites formed by fusion of sialic crustal material. However, the presence of sialic material in the Icelandic crust is known merely by inference. It is significant that the Icelandic crust is anomalous; it is neither normal oceanic nor standard continental crust. Recent geophysical studies reveal that Iceland's crust is more variable in composition and thicker than most oceanic crust (Bott, 1974). Christiansen and Blank (in press) report that the Icelandic crust is at least 15 km thick.

Mixed Lavas in the San Juan Volcanics

The volcanic history of the San Juan volcanic field of southwestern Colorado is very similar to that of the Yellowstone-Snake River Plain region. Like the Yellowstone area, the San Juan field marks the site of early Tertiary intermediate composition volcanism, followed by bimodal basaltic-rhyolitic volcanism. In addition, the bimodal volcanics of the San Juan area also contain examples of mixed basalt-rhyolite lavas.

Following an Oligocene andesitic volcanic episode, bimodal volcanism in the San Juan volcanics began in the Miocene and continued until 4 million years ago, producing a suite of alkalic basalts and silicic rhyolites. Xenocryst-bearing basaltic andesites are associated with this bimodal volcanic phase (Lipman and others, 1978, Lipman, 1971; Doe and others, 1969; Larsen and Cross, 1956; and Larsen and others, 1938). These occur as relatively homogeneous flows containing quartz and sodic plagioclase xenocrysts. The quartz xenocrysts are always rimmed by augite. The sodic plagioclase xenocrysts commonly contain clear cores surrounded by a zone of "wormy" (inclusion-filled?) calcic plagioclase, which is in turned jacketed by a thin, clear rim (Doe and others, 1969). Judging from these descriptions, the San Juan basaltic andesites resemble the Geode Creek lavas and the basaltic portions of the Gardiner River complex. The SiO_2 content of these contaminated basalts ranges from approximately 59 percent to 66 percent SiO_2 (Lipman and others, 1978).

In contrast to the homogeneity of most of the mixed lavas in the San Juan volcanics, the Handkerchief Mesa mixed lavas in the southeastern portion of the volcanic field are a heterogeneous assemblage. These variable lava flows consist of olivine basalt and silicic rhyolites. The Handkerchief Mesa lavas closely resemble the Gardiner River lavas in Yellowstone Park (Lipman, 1971, 1975; Lipman and others, 1978).

Pb and Sr isotope studies of the San Juan volcanics (Lipman and others, 1978) suggest an ultimate mantle source for both the Oligocene calc-alkaline volcanics and the Miocene-Pliocene basaltic volcanics. According to Lipman and others (1978), primary basaltic magmas formed as partial melts of mantle material. As these rising basalts heated the lower crust, silicic partial melts formed. The isotopic composition of the calc-alkalic suite indicates significant contamination of this basalt by lower and upper continental crust. On the other hand, the bimodal basaltic and rhyolitic lavas are relatively nonradiogenic, suggesting little crustal contamination. The slightly higher radiogenic Pb values for the xenocryst-bearing basaltic andesites may be due to slight contamination by the lower crust or rhyolitic magmas formed from this crust. Although the bimodal rhyolites formed as partial melts of the lower crust, they suffered little upper crustal contamination during their ascent, since they rose into a largely consanguineous batholith and were thus shielded from the ancient upper crust. The slightly different isotopic compositions of the silicic and mafic end members of the Handkerchief Mesa mixed lavas supports a mantle source of basalt and a lower crustal source for rhyolite. Christiansen and Blank (in press) note a similar isotopic difference between the basaltic and rhyolitic parents of the Gardiner River mixed assemblage which indicates separate sources for the Yellowstone basalts and rhyolites.

The plate tectonic models explaining the existence and the evolution of the San Juan volcanic field are as controversial and tentative as those proposed for the Yellowstone area. Nevertheless, there is general agreement that the early, calc-alkaline volcanic phase was somehow related to a compression-dominated complex subduction system. On the other hand, the ensuing bimodal volcanic episode developed in an extensional tectonic environment (Lipman and others, 1978). According to Lipman and Mehnert (1975), the initiation of bimodal volcanism coincides with the beginning of block faulting and the formation of the Rio Grande Rift, a major intracontinental rift separating the stable areas of the High Plains and the Colorado Plateau.

Lipman and others (1978) suggest that in the San Juan volcanics, magma mixing is controlled by tectonic setting. During regional compressional tectonics, primary mafic and silicic melts mixed thoroughly to form the intermediate composition Oligocene volcanics. However, in the Miocene-Pliocene extensional setting, these melts remained largely unmixed and rose separately as a bimodal basalt-rhyolite sequence. Local encounters between ascending basalt and rhyolite produced the San Juan mixed lavas. This magma mixing model is similar to the model proposed for the Yellowstone mixed lavas.

Mixed Lavas in the Cascades

In contrast to the extensional tectonic regime in which most mixed magmas form, the Cascade mixed lavas occur in a compression-dominated subduction zone environment. Thus at first glance, the Cascade examples seem markedly different from the mixed assemblages studied so far. However, a closer look at the Cascade assemblages reveals many similarities between the Cascade mixed lavas and the extension-related mixed assemblages. Examples of Cascade region mixed magmas include the 1915 mixed lavas and banded pumice of Lassen Peak (MacDonald and Katsura, 1965), the 1851 quartz basalts of Cinder Cone northeast of Lassen Peak (Finch and Anderson, 1930), the banded rhyodacite and mafic inclusion-charged dacites of Glass Mountain in the Medicine Lake Highland shield volcano (Eichelberger, 1974, 1975) and possibly the andesite-obsidian lavas on the north wall of Newberry caldera (Higgins and Waters, 1970). Figure 6 locates these mixed lavas.

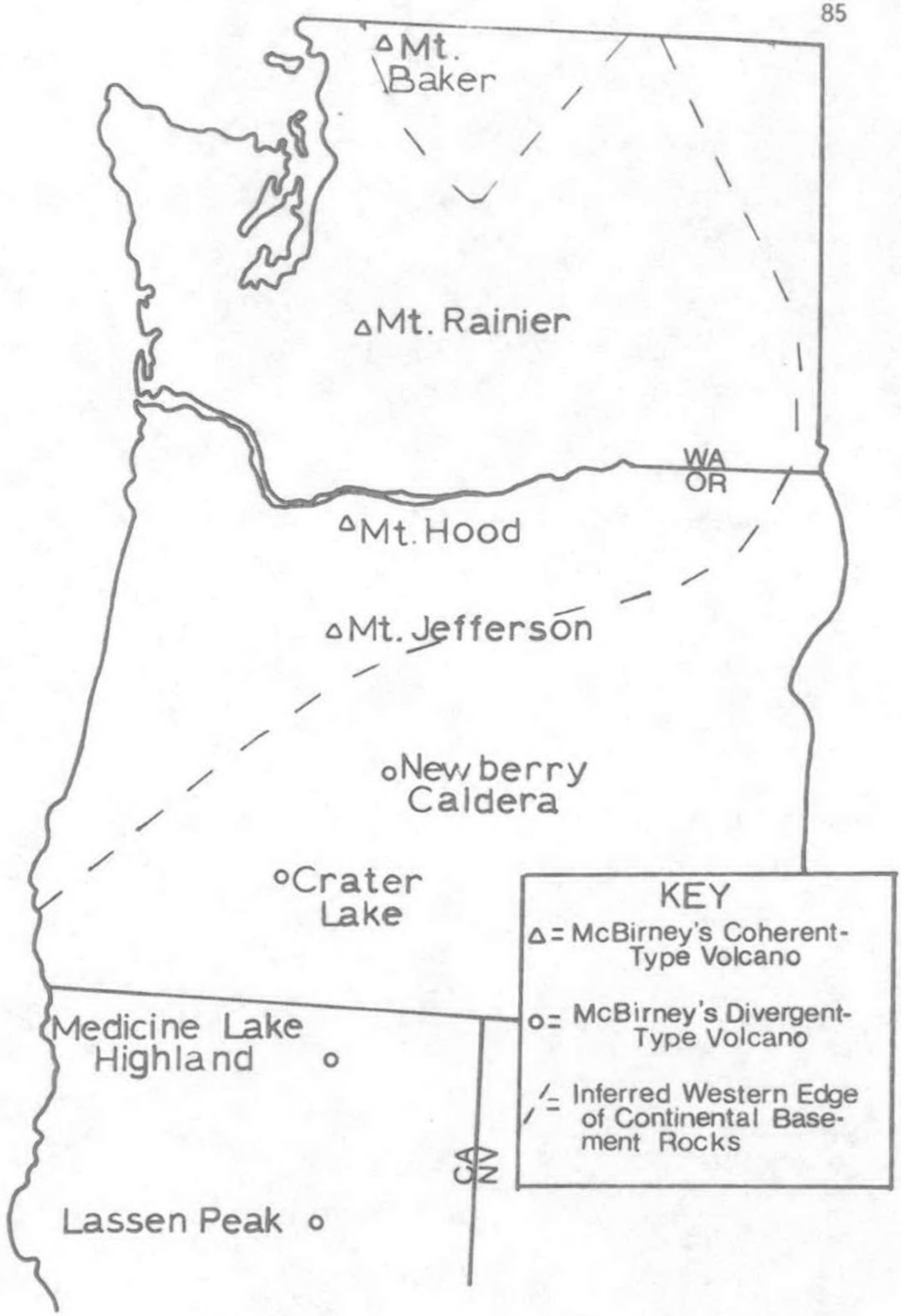

Figure 6. Map of the Cascades region. Modified after Alt and Hyndman (1978) and McBirney (1968a).

McBirney (1968a) divides the Quaternary Cascade volcanic chain into two distinct varieties based upon magma type. "Divergent-type" Cascade volcanoes, found at the northern and southern ends of the Cascade chain, consist dominantly of early cone-forming siliceous andesite or dacite, followed by flank eruptions of basalt and minor rhyolitic obsidian or pumice. Examples of divergent volcanoes include Lassen Peak, Medicine Lake Highland and Newberry Caldera. McBirney's "coherent-type" Cascade volcano, characteristic of the central Cascades, consists of monotonously uniform andesite and basaltic andesite, with minor basalt; rhyolites are conspicuously absent. Mount Rainier, Mount Baker, Mount Hood and Mount Jefferson are all coherent-type volcanoes.

According to McBirney (1968a), the difference in magma type between the divergent- and coherent-type Cascade volcanoes may be due, in part, to the position of pre-Tertiary continental basement rocks. As shown in Figure 6 most of the divergent-type Cascade volcanoes are underlain by pre-Tertiary sialic basement rocks. In contrast, the coherent-type volcanoes lie on a foundation of Tertiary mafic volcanics resembling oceanic crust. The restriction of mixed lavas to McBirney's divergent-type volcanoes is significant; it suggests that sialic basement rocks are a prerequisite not only to the formation of large volumes of silicic volcanics, but to magma mixing as well.

It thus appears that magma genesis in the Cascade region is influenced by the presence or absence of continental basement rocks.

Primary basaltic magmas form as partial melts of mantle material beneath the Cascade region. If these basalts rise into areas of sialic crust, rhyolitic magmas may form as heat from the ascending basalts partially melts the surrounding sialic basement rocks. Large quantities of rhyolitic partial melts may form in areas of fairly young, water-rich crustal rocks. As these primary basaltic and rhyolitic magmas rise through the crust, they may meet and mix, producing various compositions and proportions of contaminated basalt and contaminated rhyolite. The resulting lavas are the hybrid siliceous andesites, dacites and rhyodacites with subordinate unmixed rhyolite and basalt, characteristic of divergent-type volcanoes. On the other hand, basalts generated beneath areas of mafic, oceanic crust suffer little or no contamination as they rise to the surface. The basalts and basaltic andesites of the coherent-type volcanoes form in this manner. It should be noted, however, that the basaltic andesite so common in the central Cascades may not be a primary magma. These pyroxene andesites may represent slight contamination of primary, mantle-derived basalt by trench or accretionary prism-type sediments (Alt, 1978, verbal communication).

Magma mixing in the Cascade region thus occurs on a large scale to produce intermediate composition volcanic rocks. Walker and Skelhorn (1966) suggest that many volcanic arc andesites are hybrid lavas formed by the mixing of primary mafic and silicic magmas. Abundant and varied phenocrysts, displaying disequilibrium features such as reaction rims and zoning are common in arc andesites. The formation of this diverse phenocryst assemblage may be easier to explain by mixing of two contrasting porphyritic magmas than by differentiation in equilibrium from one liquid. Mixing in this environment produces a fairly homogeneous, well-mixed, intermediate composition hybrid lava. On the whole, the siliceous andesites and dacites typical of divergent Cascade volcanoes are uniform (McBirney, 1968a). Thorough mixing in the Cascade subduction environment is aided by relatively high magma water contents, which lowers magma viscosities thereby encouraging diffusion, and by a relatively deep site of mixing, allowing thorough mechanical stirring and mixing as the magmas ascend to the surface. These homogeneous, divergent-type siliceous andesitic and dacitic volcanics are not commonly considered mixed magmas.

Magma mixing in the Cascades also occurs on a small scale, producing the well-known, locally developed mixed magmas such as the Lassen Peak, Cinder Cone, Glass Mountain and Newberry examples. This type of magma mixing differs radically from the relatively deep-seated mixing process just described. Small-scale mixing apparently occurs at shallow levels, as suggested by the association of these mixed lavas with shallow magmatic features such as calderas and late-stage silicic domes. The diapiric rise of magma into these shallow crustal levels may produce local sites of extensional tectonics within a regional environment of compressional, subduction-style tectonics. In this manner, the immediate tectonic setting of the Cascade mixed lavas is similar to the extensional environment common to most mixed lavas. In contrast to the well-mixed, homogeneous lavas produced by deep-seated magma mixing, shallow mixing commonly produces poorly-mixed assemblages in which the mafic and silicic parents remain as recognizable components. The 1915 light and dark banded pumice of Lassen Peak, and the Glass Mountain banded rhyodacite with mafic inclusions are examples.

Magma mixing at shallow levels within a subduction zone commonly involves dry magmas which have already vented most of their volatile components. The high viscosity of volatile-poor magmas inhibits thorough mixing by limiting diffusion. Apparently many of the Cascade mixed magmas are fairly anhydrous. Williams (1931, 1932) notes the lack of water and high viscosity in both the 1915 Lassen Peak lavas and the 1851 Cinder Cone quartz basalts. Complete homogenization of magmas that mix at shallow levels is further inhibited by the short travel distance between the site of mixing and the surface, thus limiting the amount of mechanical stirring prior to eruption.

A controversy surrounds the origin of the "basalt"-obsidian lavas at Newberry Caldera. The andesitic scoria, flows and agglutinate on the north wall of Newberry Caldera carry abundant inclusions of platy rhyolite, partly melted platy rhyolite and frothy obsidian. Williams (1935) interpreted this "basalt"-obsidian association as an example of mixed basalt and rhyolite. However, recent investigations suggest that these fragments were ripped from a rhyolitic portion of the caldera wall during eruption of the andesitic lavas. In this manner, these lavas do not represent mixed magmas (Higgins and Waters, 1970). Nevertheless, the andesitic lava is contaminated by the partially melted rhyolitic inclusions. Eichelberger (1974, 1975) considers this type of magma contamination, the modification of a lava by glassy debris in the pre-existing volcanic pile, as a common and important process. It should be noted that Newberry Caldera lies approximately 50 km east of the main Cascade volcanic chain. As such, Newberry may be an atypical Cascade volcano (Alt, 1978, verbal communication).

The Cascade mixed assemblages exhibit many features similar to those described in the Yellowstone mixed lavas. The compositionally zoned lava flow at Glass Mountain is an example of basaltic contamination of a rhyolite, similar to the Gardiner River lavas. The Glass Mountain flow grades from uncontaminated rhyolite, to rhyolite with basaltic inclusion and mafic bands, to a highly contaminated and well-mixed dacite. Eichelberger (1974, 1975) argues that the Glass Mountain rhyolite was contaminated by solid, glassy basaltic material in the Medicine Lake Highland shield volcano as the rhyolite rose towards the surface. However, the contamination features observed at Glass Mountain, including inclusions of porphyritic basalt in rhyolite and dacite, are similar to those features produced by mixing liquid basalt with liquid rhyolite, and many have formed in this manner. On the other hand, the 1851 quartz basalt flows at Cinder Cone, northeast of Lassen Peak, formed by the addition of rhyolite to a basalt, and closely resemble the Geode Creek assemblage. Finch and Anderson (1930) report rounded and corroded quartz xenocrysts rimmed by augite at Cinder Cone. They also describe zoned and inclusion-filled plagioclase crystals like the Geode Creek plagioclase xenocrysts. Similarly, the banded pumice and mixed lava flows produced by the 1915 eruption of Lassen Peak contain plagioclase grains with irregular, inclusion-filled cores and euhedral, thin, clear rims (MacDonald and Katsura, 1965). These bear close resemblance to the Geode Creek plagioclase xenocrysts.

Magma mixing in the Cascades may be much more common than is currently recognized. In addition to the well-known examples of Cascade mixed lavas, other volcanics in the Lassen Peak area are probably unrecognized examples of mixed lavas. Both the pre-Lassen dacite flows and the Lassen Peak dacite dome carry abundant mafic inclusions. Williams (1931) contends that these inclusions are early, mafic precipitates torn from the magma chamber walls during eruption. However, the high glass content of these inclusions and their similarity in composition to nearby mafic lavas suggests that the Lassen dacites formed by the contamination of silicic magma by a mafic magma (Eichelberger, 1975). The very dry and viscous nature of the Lassen dome dacite may explain the poorly mixed aspect of this lava.

In review, magma mixing is common in the Cascade volcanics. However, its importance remains largely unrecognized. Large-scale, complete mixing of primary basaltic and rhyolitic magmas may play a large role in the generation of "divergent-type" Cascade andesitic and dacitic lavas. On the other hand, local examples of small-scale, incomplete mixing are widespread throughout the Cascades, although their abundance may be underestimated.

Summary

A comparison of the Yellowstone mixed assemblages with mixed lavas in the British Isles, Iceland, the San Juan Mountains and in the Cascades reveals many tectonic and petrologic similarities among mixed lavas throughout the world. Consideration of these similarities leads to the magma models discussed in the following chapter.

CHAPTER XI

TECTONIC AND PHYSICAL CONTROLS ON MAGMA MIXING

Tectonic Setting of Magma Mixing

Most of the examples of magma mixing discussed in this study have an obvious feature in common; except for the Cascade assemblages, these lavas all formed in an extensional tectonic setting. The examples cited from Yellowstone National Park, the San Juan volcanics, and the British Tertiary province all developed in a continental rifting environment. The Icelandic varieties formed in an oceanic rifting environment, although as previously explained, Iceland may be underlain by anomalous oceanic crust. Recent studies by Dungan and others (1977) suggest that magma mixing also occurs in areas of more conventional oceanic crust. They propose that some oceanic rise tholeiites are a hybrid lava. In contrast to these rifting related mixed lavas, the Cascade examples are spatially related to an active subduction zone. Thus at first inspection, it appears that mixing of basalt and rhyolite occurs both at rifting and subduction related environments. Since the mixed lavas produced in these two different tectonic settings share many similarities, it follows that there must be a physicochemical condition or set of conditions similar in both environments that controls mixing of basalt and rhyolite.

The physical parameter common to both the Cascade mixed lavas and the rifting mixed lavas is depth of magma mixing. In both of these environments, mixing occurs at very shallow levels within the crust. It is this factor, shallow sites of mixing, rather than the specific tectonic environment, that plays the most important role in the mixing and subsequent contamination of basaltic and rhyolitic magmas.

There is ample evidence suggesting that magmatic processes take place at shallow depths in extensional terranes. Magmatism is clearly shallow in Iceland, an active oceanic rift zone, underlain by thin crust. Shallow magmatism in areas of continental extension can be inferred from several factors. Many continental rift zones are dominated by calderas, ring dikes, cone sheets and other shallow magmatic structures. Such features are common throughout the British, San Juan Mountains, and Yellowstone extensional terranes. For example, Eaton and others (1975) provide geophysical evidence indicating active magmatism in Yellowstone Park at depths of only a few kilometers.

On the other hand, magma genesis in subduction zones occurs at depths of 50 to 150 kilometers, in the vicinity of the low velocity zone of partially melted mantle material (Hyndman, 1972, p. 125, 178). However, as seen above, areas of local shallow magmatism do occur within a subduction zone. The Cascade mixed lavas are associated with this type of shallow magmatism. Thus even though the Cascade mixed assemblages are spatially related to a subduction zone, these lavas, or at least mixing of these lavas, occurred at shallow levels in the crust. Thus, the mixing process is not genetically related to subduction-style magmatism and tectonics.

In this manner, extensional tectonic settings are the most typical environments of magma mixing since shallow magmatism is common in rift environments. Mixed basalt-rhyolite lavas are more unusual in subduction environments where magma is generated at depth. However, isolated shallow level magma chambers within a subduction zone are also favorable environments of magma mixing.

Physicochemical Controls on Magma Mixing

It is necessary to consider the physical and chemical aspects of shallow magmatism that might control magma mixing. These factors include: low P_{H_2O}, low water content, high viscosity, restricted diffusion of constituents, and limited time for contact and mixing of two magmas prior to eruption.

Magma water contents depend partially upon the depth of magma genesis. Shallow magmas characteristic of rift zones are fairly dry, due in part to frequent surface venting of volatiles. These magmas have low P_{H_2O} due to their low water content. Deeper magmas, such as those generated within a subduction zone, are commonly wetter than shallow magmas. This difference in water content between subduction zone and rift zone magmas can be evaluated by considering the contrasting P_{O_2} of calc-alkaline, subduction zone basalts and the P_{O_2}

of tholeiitic, rift zone basalts. P_{O_2} is a rough measure of magma water content. A high P_{O_2} implies a high water content; a low P_{O_2} indicates a fairly dry magma. The P_{O_2} of a magma determines the oxidation state of iron in the magma. Iron is oxidized in conditions of high P_{O_2}, and is removed early during differentiation as magnetite. In magmas of low P_{O_2}, iron remains reduced and forms late-stage ferrous silicates. Tholeiitic basalts have low P_{O_2} and become enriched in iron during differentiation. However, calc-alkaline basalts experience no such enrichment since they have a high P_{O_2} (Hyndman, 1972, p. 80). Figure 7 illustrates this difference in the behavior of iron in tholeiitic and calc-alkaline suites. Although this contrast in water content between rift zone tholeiitic basalts and subduction zone, calc-alkaline basalts may be an expression of depth of magma genesis, it may also be a function of the water content of the source materials of tholeiitic and calc-alkaline basalts. Tholeiitic basalts may form from a drier source than subduction zone basalts.

Magma viscosity is largely controlled by magma water content. Dry magmas have a high viscosity because of the high degree of polymerization of silica tetrahedra. Higher water contents inhibit polymerization by bonding of hydrogen ions to the oxygen corners of silica tetrahedra, thus reducing magma viscosity (Hyndman, 1972, p. 74). In general, high viscosity limits diffusion of magma constituents. Thus when shallow, dry basalt and rhyolite meet, the high magma viscosities and corresponding slow rate of diffusion inhibit thorough mixing and

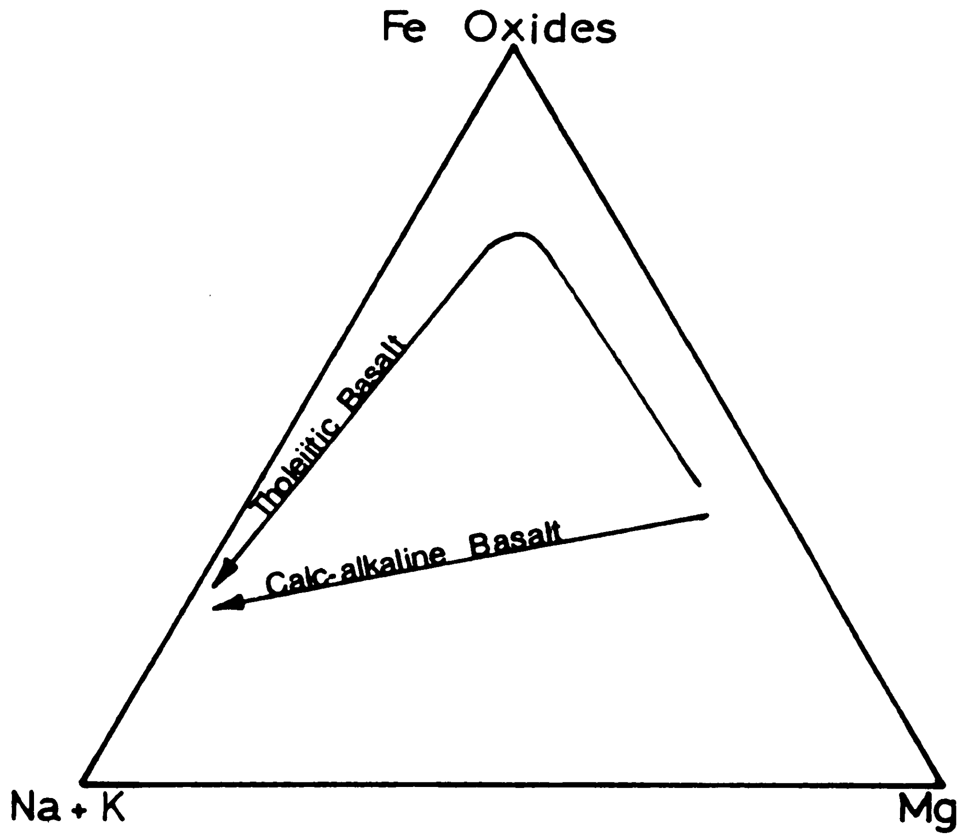

Figure 7. Contrasting differentiation trends and oxidation states of iron for tholeiitic (rift zone) basalts and calc-alkaline (subduction zone) basalts. (Hyndman, 1972, p. 80).

homogenization of these two magmas. The resulting lava is an inhomogeneous hybrid assemblage typified by the Gardiner River lavas. The more homogeneous Geode Creek lavas are no exception to this theory. Their near homogeneity can be readily explained by considering the thermal constraints involved when rhyolite contaminates basalt. Basalt can chemically assimilate a rhyolite contaminant, producing a fairly homogeneous hybrid rock assuming ample time for equilibrium.

A corollary following from the above argument that complete mixing is inhibited in dry, viscous, shallow magmas is that wetter, less viscous magmas with higher rates of diffusion should be well mixed. During their ascent through the crust, subduction zone magmas may incorporate significant amounts of water by partially melting water saturated continental crust and accretionary prism sediments (Hyndman, 1972, p. 124). Thus, mixing of primary basaltic and rhyolitic melts in these deep, water-rich conditions should produce a more thoroughly mixed, nearly homogeneous hybrid lava. As mentioned above, fairly homogeneous arc-andesites commonly exhibit petrographic evidence of disequilibrium similar to those disequilibrium features described for mixed magmas. In this manner, some arc-andesites may form as water-rich basaltic and rhyolitic melts thoroughly mix at depth.

The time interval between initial contact of basaltic and rhyolitic melts and eruption is presumably another important factor controlling the degree of mixing and homogenization. Generally, this is a function of the depth to the site of mixing. In an extensional environment, where magmatism is shallow, the distance or travel time between the site of mixing and eruption is relatively short, thus limiting the opportunity for complete mixing. An inhomogeneous hybrid lava results. In contrast, basalt and rhyolite may meet at deeper levels within the crust in a subduction zone setting. This increase in distance or travel time from the site of mixing to the surface allows greater opportunity for mechanical stirring and complete mixing, resulting in a nearly homogeneous lava.

Bimodal Volcanics as Unmixed Rocks

Pursuing this line of reasoning that mixing is limited in shallow, dry magmas and more complete in deeper, wetter magmas, may partially explain the puzzling phenomenon of bimodal volcanism. Bimodal volcanic provinces are commonly dominated by an extensional tectonic regime and shallow, dry magmatism. As explained above, diffusion and mixing are limited in this environment. Thus, the quantities of largely unmixed basalt-rhyolite lavas blanketing extensional terranes throughout the world may be explained by the inability of these magmas to mix well in the shallow, dry magmatic environment characteristic of extensional settings. As suggested by the Cascade mixed assemblages, however, shallow, dry magmatism can occur in other tectonic settings as well. In this manner, those mixed basalt-rhyolite assemblages outcropping in bimodal terranes are anomalous, for the physical conditions of extensional magmatism most commonly produce an unmixed, bimodal suite. This accounts for the comparative rarity of mixed lavas in bimodal volcanic fields. A schematic illustration of bimodal volcanism and limited magma mixing in an extensional terrane is shown in Figure 8.

On the other hand, the physical parameters of deeper magmatism, such as that common in subduction zones, favor more complete mixing and homogenization. Thus mixing basaltic and rhyolitic melts deep within a subduction zone, or any setting with similar physical conditions, usually produces a well mixed lava of intermediate composition. In this manner, magma mixing may play a significant role in the generation of subduction zone andesites. Figure 9 illustrates complete magma mixing at depth within a subduction zone, and limited mixing at shallow levels in this environment.

It must be noted, however, that rhyolitic magmas should form by partial melting of the lower crust in extensional terranes as well as subduction zones. Following the above argument, this deep level rhyolite should mix with rising basaltic magma and form andesitic volcanics. The absence of intermediate lavas in bimodal terranes presents a serious obstacle to the proposed magma mixing scheme and its application to the process of bimodal volcanism.

There are several partial solutions to this problem. First, where the lower continental crust is composed of anhydrous, granulite facies, metamorphic rocks of roughly granitic composition, a dry rhyolitic melt

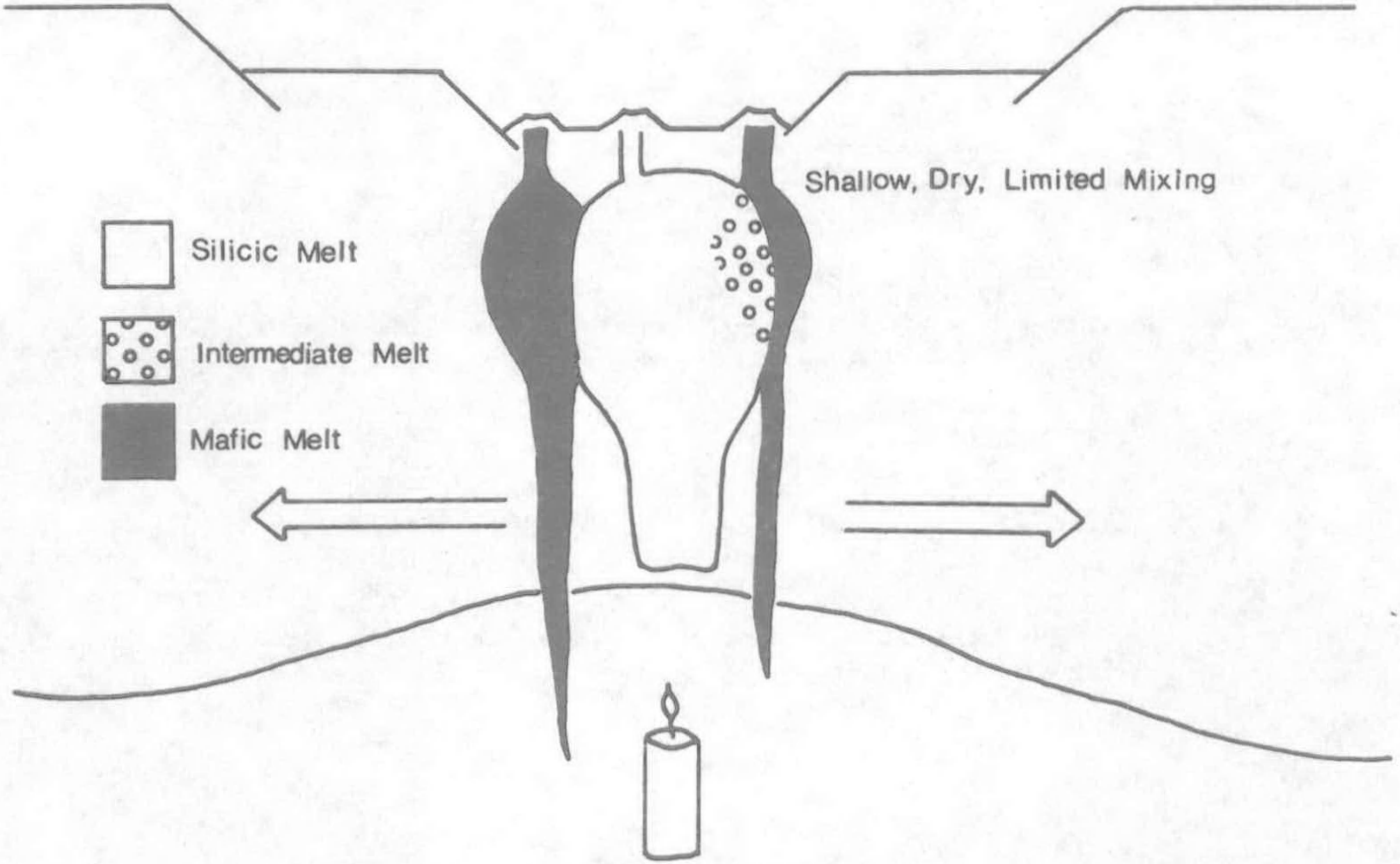

Figure 8. Magma mixing in an extensional, bimodal volcanic terrane.

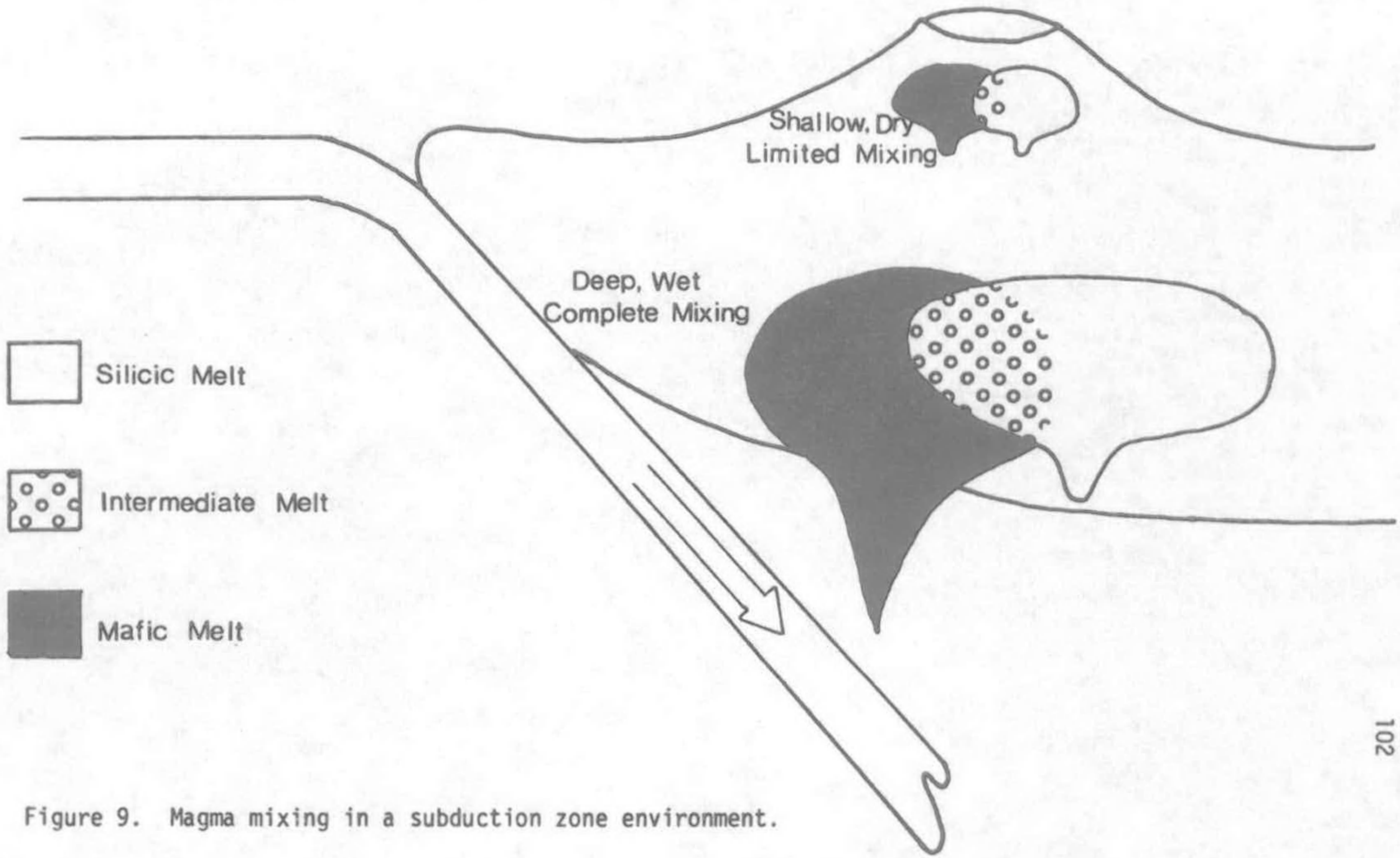

Figure 9. Magma mixing in a subduction zone environment.

will form by partial melting of this crust. This deep, dry melt will have the same mixing-limiting factors as shallow, dry magmas. Rifting of Precambrian metamorphic terranes may well involve lower crustal rocks of granulite facies composition. Second, extension causes stretching and thinning of the continental crust. Thus, the continental crust in an extensional terrane may be anomalously thin. Partial melting of this thinned crust produces shallow level rhyolitic melts.

Eichelberger (1974) also proposes that the degree of magma mixing is controlled by tectonic setting. Eichelberger's model involves contamination of rising, primary basaltic and rhyolitic melts by the easily melted, glassy lavas in the volcanic pile. As the volcanic pile thickens, the opportunity for magma contamination and hybridization increases. Thick volcanic sequences characteristic of stationary and prolonged subduction zone volcanism are thus composed of mixed, hybrid lavas of intermediate composition. The base of these piles, however, will be bimodal. On the other hand, the migrating volcanism typical of continental rifting, produces a thinner sequence of largely unmixed basalts and rhyolites.

Bimodal Volcanism and Silicate Liquid Immiscibility

Many workers have surmised that silicate liquid immiscibility governs the generation of unmixed, bimodal volcanics. Recent studies by Roedder (1977) suggest that under certain conditions rhyolitic and basaltic melts do exist as two separate, immiscible liquid phases.

Philpotts (1971, 1976) reports liquid immiscibility in some lunar rocks, alkalic systems and perhaps granophyric rocks. The lack of mixing between deep level basaltic and rhyolitic melts formed in extensional terranes is perhaps another example of silicate liquid immiscibility. There is ample outcrop evidence that basaltic and rhyolitic melts can coexist in the same magma chamber. The Pinnacles at Crater Lake National Park in southern Oregon provide spectacular proof. These spires, formed by a glowing avalanche deposit, consist of white dacite pumice at the bottom, which changes abruptly to a hornblende scoria. Clearly the magma chamber responsible for this event was compositionally zoned with dacite on the top and mafic magma below (McBirney, 1968b). However, the likelihood of silicate liquid immiscibility as a controlling factor in bimodal volcanism is diminished in shallow magmas in which the lack of mixing is more readily explained by slow diffusion rates and lack of opportunity for mixing.

CHAPTER XII

SUMMARY AND CONCLUSIONS

Mixed lavas are widespread; they outcrop in numerous volcanic terranes. However, mixed assemblages comprise a minute portion of these volcanic piles. This paucity of mixed lavas may reflect the difficulties involved in identifying some mixed magmas. The evidence for magma mixing can be quite subtle, and is commonly overlooked. Disequilibrium textures characteristic of mixed lavas occur in many volcanic rocks. These features are usually interpreted as evidence of disequilibrium differentiation. However, a magma mixing model for these lavas is compatible with the observed petrographic features. Magma mixing may thus be much more common than is currently realized. As suggested by Walker and Skelhorn (1966) some arc andesites may be hybrid magmas formed from the mixing of silicic and mafic melts. Unrecognized mixed magmas may also occur in extensional, bimodal volcanic terranes. For example, the Madison River basalts in Yellowstone National Park are anomalously silica-rich compared to nearby basalts, and may represent a hybrid composition. Future studies of magma mixing should focus upon these potential examples of mixed magmas.

The degree of magma mixing ranges from well-mixed, nearly homogeneous intermediate composition lavas to poorly mixed, heterogeneous volcanics. Mixing at depth of water-rich magmas apparently produces well-mixed magmas. Mixing is more limited in shallow, dry magmatic environments.

The tectonic setting of magma mixing is variable. Poorly mixed magmas most commonly develop in extensional, bimodal volcanic provinces. However, they are locally developed at shallow levels within subduction zones as well. Well-mixed magmas generally form at deep levels in a compressional, subduction zone environment.

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